INVESTIGATION OF HEAD MOVEMENT AND INTENSITY AS DEPTH CUES IN A PERSPECTIVE CONTACT ANALOG DISPLAY

by

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Chairman, Departmental Graduate Committee

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ABSTRACT

To determine the depth cue value of head movement perspective, and image intensity as a function of depth, an experimental investigation was conducted.

A contact analog 3-D Display System was programmed on a hybrid computer. A line drawing of a single cube fixed in space was displayed on a CRT screen as if the screen were a window. This was accomplished by using the equations of linear perspective for a monocular observer whose head position is variable with respect to the screen. Motions of the vehicle, containing the observer and screen, were simulated using the six velocities in body fixed axes.

An experiment was conducted to determine the amplitude of a sinusoidal voltage applied to the CRT intensity grid as a function of line length, so that lines drawn in constant time intervals would have an apparent brightness independent of line length.

Depth discrimination experiments were conducted using the perspective display with combinations of head movement and cube intensity as a function of depth. The cube was displayed as if it were at one of a set of discrete depths and the subject asked to identify that depth. The resulting stimulus-response matrices were analyzed to determine the information transmission. It was found that head movement gives a 40 percent improvement in depth discrimination when the cube is between 50 and 100 cm from the subject. Head movement is four times more helpful when the cube is between 50 and 100 cm from the subject than when the cube is between 150 and 300 cm. Intensity variation resulted in half as much improvement as head movement.

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The author thanks the members of the M.I.T. Man-Vehicle Control Laboratory who participated in the initial 3-D Display System programming effort. Special thanks are extended to Noel Van Houtte for programming the logarithm and antilogarithm subroutines and portions of the program to analyze the stimulus-response matrices, and to Charles M. Oman for the work on rotation and blanking algorithms.

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CHAPTER 1

INTRODUCTION

Each new generation of vehicles produced has a higher performance than previous generations. Significant improvements are being made in the performance of V/STOL aircraft, conventional aircraft, helicopters, supersonic aircraft, manned spacecraft, undersea craft, and surface ships. All of these vehicles need some display for navigation, guidance, and control during all phases of a voyage.

It is desirable to have these higher performance vehicles follow a prescribed path, or reach a prescribed point, more accurately than previous generations of vehicles. Some considerations leading to this desire are: (1) safety in high density traffic patterns, (2) rise in cost as the actual path deviates from the optimum, (3) landing at an airport among tall buildings in the urban center, (4) low level terrain avoidance flying, (5) orbital or undersea rendezvous and docking, and (6) maneuvering at high speed to avoid turbulence, icebergs, or other obstacles. It also becomes more important to be able to operate these high performance vehicles, with the same path following accuracy, in zero-zero visibility because of the high additional cost of delaying the voyage.

As these vehicles have achieved higher levels of performance, they have become increasingly complex. This means closely monitoring the value of more parameters and the functioning of more components. In some cases the increased performance was obtained with a reduction in stability. This required stability augmentation systems and more indicators to be closely monitored.

It is difficult to watch several instruments at once and control the vehicle to follow the desired flight path. When the outside world is not visible, it is even more difficult to integrate the information from the instruments into the three dimensional situation, or "big picture" of the position, orientation, and velocity, in relation to the desired path. If the three dimensional situation is not perceived in a sufficiently clear and compelling way, the pilot may experience vertigo, or disorientation, when his other sensory information appears to conflict with his perception of the situation.

Progress has been made in the display field. Most of this progress has been making instruments to display several parameters on a single dial face in an integrated form and locating instruments where they are more conveniently seen. Such improvements are the crossed needles of the ILS glide-path and localizer indicator, the three-degree-of-freedom attitude "eight ball," horizontal and vertical situation displays, and head up displays. These displays have improved the pilot's ability to control his vehicle and follow the specified flight path.

There are areas where improvements need to be made in displays. Further integration by the pilot is still required to get the three dimensional situation before interpreting it. The task of keeping pointers in certain positions on dials bears little resemblance to the reality of following a three dimensional path. The accuracy of following a specified three dimensional path decreases as its complexity increases, because that path is not presented in an easily understandable way, and the deviation of the vehicle from that path is not immediately apparent.

The best means for a pilot to determine the full three dimensional situation is looking out the window, or contact flying, if visibility permits. This suggests that the best 3-D situation display would be an analog of the view through the window, or contact analog display. Most existing contact analog displays have not produced the anticipated improvements in performance.

Contact analog displays have the potential to equal or surpass the performance obtained when flying under VFR conditions because: (1) the 3-D situation can be presented in a visually compelling way, (2) the desired 3-D flight path can be presented in a more realistic way and faster than reference to a large manual, (3) the desired path can be shown ahead of the vehicle to allow use of predictive control techniques by the pilot, (4) path changes resulting from ground approach control decisions or turbulence avoidance requirements can be quickly presented, in an easily understandable way, and (5) they can be just as helpful in zero-zero visibility.

Of course, even with a contact analog display, some quantitative readouts would be necessary for the pilot to adequately handle the control task. Alternatively, more of the control task could be performed by automatic systems. In this case the pilot needs a display for monitoring the performance of the automatic systems. The contact analog display would be just as valuable for monitoring as for manual control. With the use of a contact analog display, deviations from the flight path could more easily be detected and the appropriate corrective action would be more apparent.

One of the more convincing analog displays of the real world, that has been built and demonstrated, is a binocular, head-mounted television display system[2]. The screens were fixed to the observer's head and the camera servo driven to duplicate the motion of the observer's head. This system was too heavy and restricted the pilot too much, to be used in an aircraft, and would not work in zero-zero visibility.

But it did show that an analog display could seem very real and present the 3-D situation convincingly.

The computer driven display is the best implementation of a contact analog system. The visual display space available is then highly plastic and may be changed in an adaptive fashion to meet varying display requirements during the flight. The computer can process the outputs of inertial sensors, radar, and other inputs from the vehicle, to generate the required display.

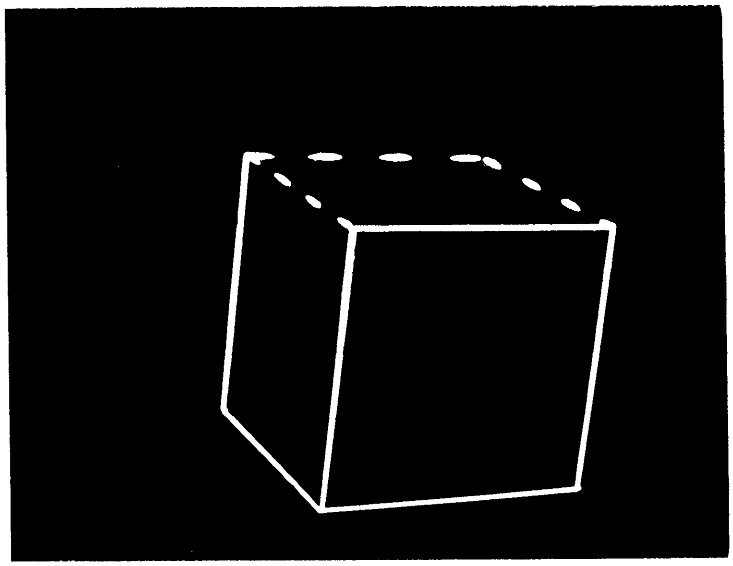
The questions that need answering are how to represent the real world and how to change the display of that representation as the vehicle moves so that adequate cues are provided to help the pilot. There are many possible cues for depth perception from a two dimensional image of the 3-D world[7,8,12,13]: linear perspective from a point fixed with respect to the display screen, linear perspective from the actual (and variable) position of the pilot's head, stereopsis (the psychophysical perception of depth through fusion of the disparate retinal images), accommodation (focusing of the eyes), shadows, interposition (occlusion of one object by another), resolution of detail and surface texture, inverse square law of illuminance, and loss in clarity due to the intervening air mass.

In order to answer some of the above questions, a 3-D Display System[14] was programmed on the PDP-8--GPS 290T hybrid computer[4,6]. The simplified representation of the real world was a single cube. The depth cues provided were linear perspective, both for a point fixed with respect to the screen and for a variable point (head motion), and variable intensity of the image as a function of the distance from the observer's eye to the cube.

The observer, or "pilot," was provided with control stick inputs to a set of analog dynamics. The translational and rotational velocities of the vehicle (in the vehicle fixed coordinate system) were used by the digital computer to update the positions (in the vehicle fixed coordinate system) of the corner points of the inertially fixed cube. The perspective view of the cube was determined and displayed as a line drawing on an oscilloscope. A detailed description of the 3-D Display System is presented in Appendix A.

The edge lines hidden by the cube's own volume were not displayed. It was found necessary to omit the hidden lines because perspective reversals, accompanied by apparent rotation reversals, occurred too frequently when all lines were displayed. Perspective reversal is the visual illusion that the rear of an object is closer than the front. The Necker Cube[3] is a well-known example of the phenomenon.

Since the cube is symmetric it was necessary to provide additional cues to allow determination of the cube's attitude so that ambiguities in vehicle position could be resolved. This was done by presenting three edges of one face as dotted lines, as shown in Figure 1.1.



5 cm

FIGURE 1.1 THE CUBE WITH THREE EDGES DOTTED

The equations of linear perspective that transform a point in three dimensional space onto a two dimensional screen are

$$h = \frac{B - x_{hd}}{x - x_{hd}} y + \left(1 - \frac{B - x_{hd}}{x - x_{hd}}\right) y_{hd}$$

$$v = \frac{B - x_{hd}}{x - x_{hd}} z + \left(1 - \frac{B - x_{hd}}{x - x_{hd}}\right) z_{hd}$$

where h and v are the screen coordinates (the H axis is parallel to the Y axis, V is parallel to Z, and X is perpendicular to the screen through h=0, v=0), B is the position of the screen on the positive X axis, x, y, z are the three-space coordinates of a point, and x_{hd}, y_{hd}, z_{hd} are the three-space coordinates of the observer's head. The 3-D Display System used only lateral head position, that is

$$x_{hd} = z_{hd} = 0$$

and

$$h = \frac{B}{x} y + \left(1 - \frac{B}{x}\right) y_{hd}$$

$$v = \frac{B}{x} z$$

The geometry is shown in Figures 1.2 through 1.4 for the horizontal screen coordinate equation. The equations express the fact that the line of sight is straight and that the point to be displayed is the intersection of the line of sight with the screen.

Figure 1.2 illustrates the cues resulting from perspective with head position assumed fixed ($y_{hd} = 0$). The apparent size of the object decreases as B/D, where D is X coordinate of the object. Thus the screen image of object 1 is larger than object 2. Lateral (Y) displacements of the object result in apparent displacements, but the gain on the displacement is also B/D. Thus the screen image of object 2 is closer to the center of the screen than the image of object 1. This gain on displacement is also effective from front to back on the object. That is, the front will have a larger apparent lateral displacement than the back, which results in an apparent rotation. If L is the lateral displacement of the object, then the apparent rotation may be expressed as $\tan^{-1}$ (L/D). With these cues, the three-space orientation of the object may be readily inferred from the two dimensional screen image.

Figure 1.3 illustrates the additional cues resulting from including lateral head movement, y_{hd}. Now there is an additional apparent displacement due to lateral head movements, $(1 - B/D)\ y_{hd}$. There also is apparent rotation due to head movement, $-\tan^{-1}\ (y_{hd}/D)$. Since the pilot can judge the position of his head with respect to the screen, or "window," he gets additional information from the combination of apparent rotations and translations. Also, the object should seem more real to the observer with head movement because the

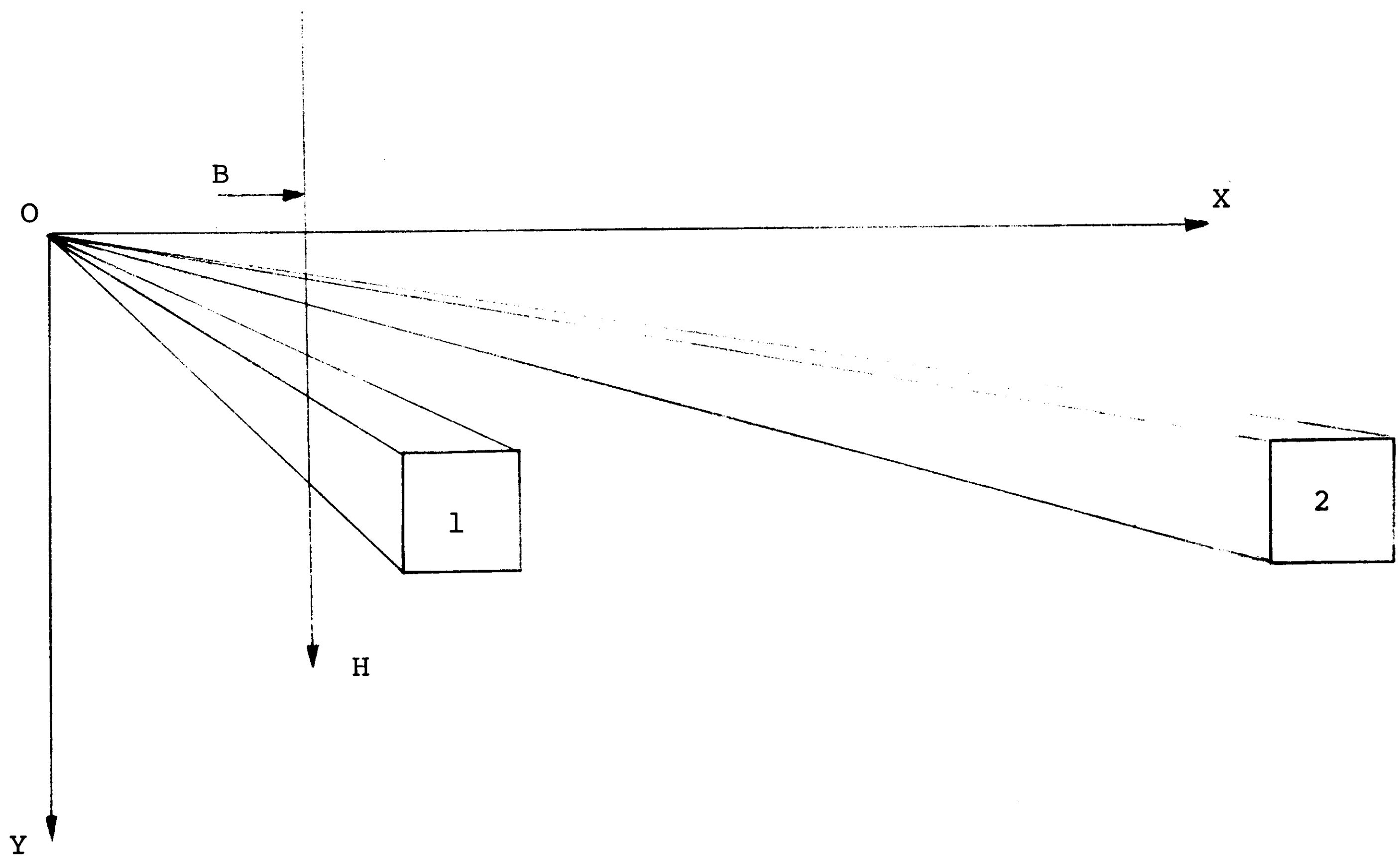


FIGURE 1.2 PERSPECTIVE FROM A FIXED POINT

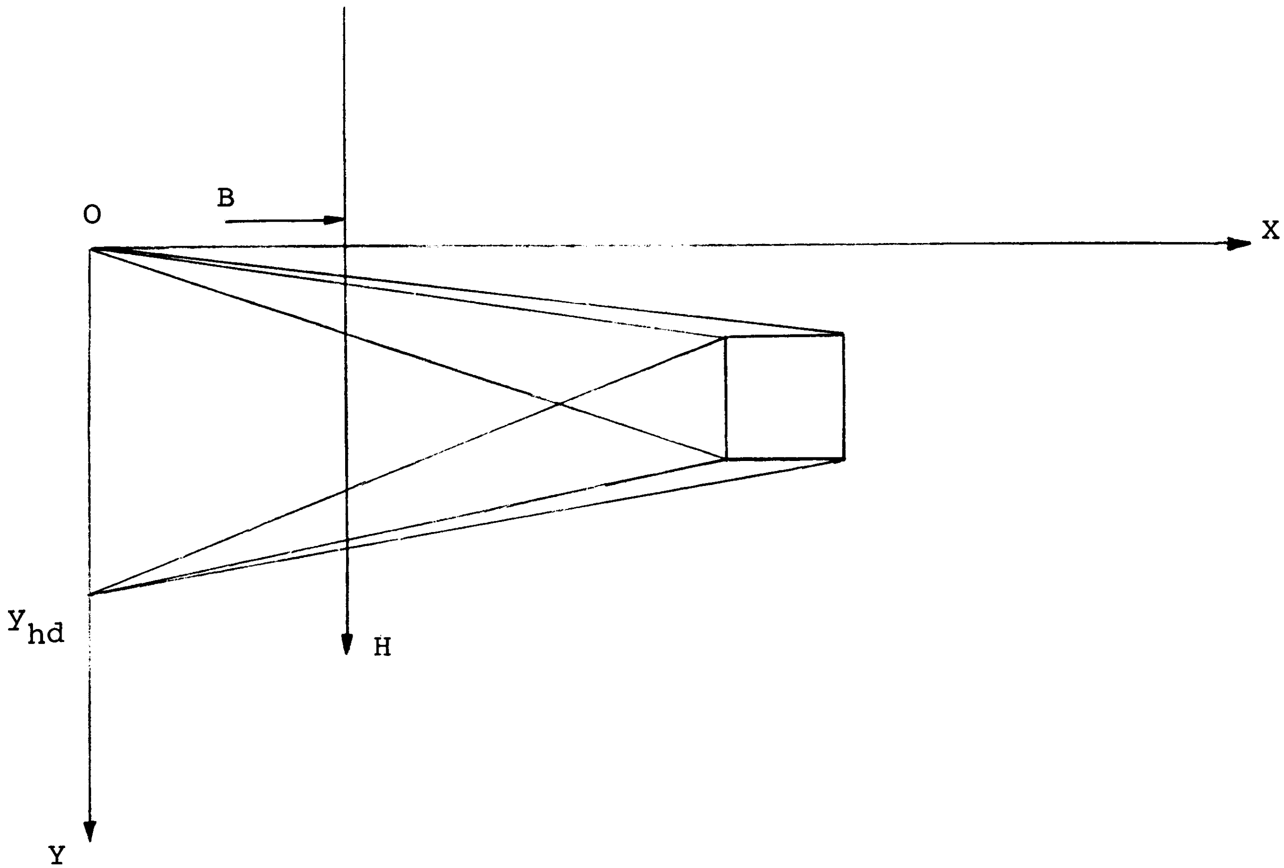


FIGURE 1.3 PERSPECTIVE CHANGES RESULTING FROM LATERAL HEAD MOVEMENT

display screen behaves as if it were a window rather than just a picture.

Another way of considering the effects of perspective with head movement is the change in the field of view. This is illustrated in Figure 1.4 where the window is located between $-h_e$ and $+h_e$, its edges. As the object is farther behind the screen, it occupies a smaller fraction of the field of view. Hence, it appears smaller. As the object is farther behind the screen, the lateral displacement is a smaller portion of the field of view. Hence, the object appears to be closer to the center of the screen. The conclusions reached from field of view analysis are the same as in the previous paragraphs, but provide more insight to multiple-object displays or the continuum of the real world. As the observer's head moves to the right, he sees objects leave his field of view at the right edge of the window and enter from the left. They enter more rapidly as D increases. Thus, the change in field of view can serve as an additional depth cue in multiple object displays. This is a more commonly experienced phenomenon than the apparent motions of a single object, and, as a result, multiple-object perspective displays with head movement are likely to produce a stronger sensation of reality than single object displays.

The goal of this thesis is to quantitatively compare the depth perception resulting from three visual cues. The cues investigated are: (1) linear perspective from a fixed

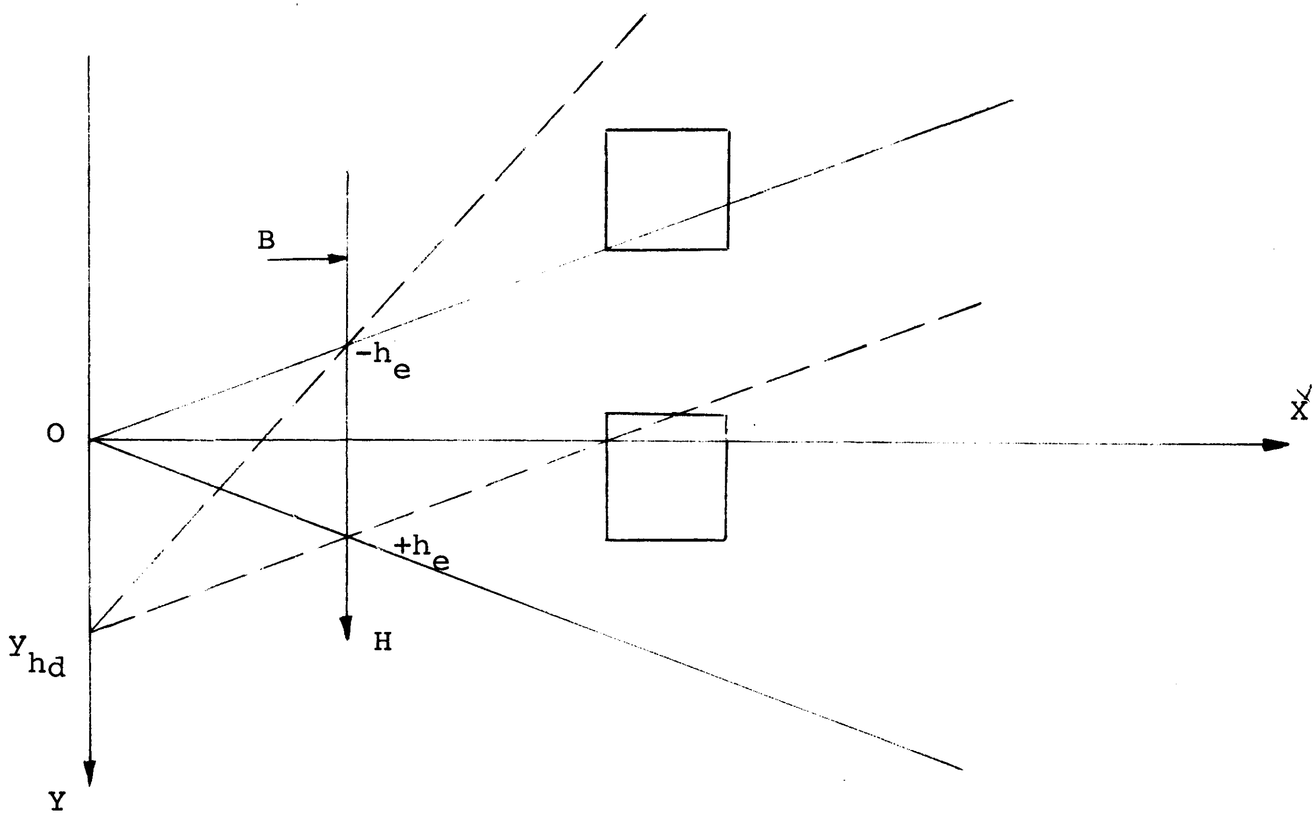


FIGURE 1.4 PERSPECTIVE CHANGES AS CHANGES IN THE FIELD OF VIEW RESULTING FROM LATERAL HEAD MOVEMENT.

head position, (2) linear perspective from the measured lateral position of the subject's head, and (3) intensity proportional to the inverse square of the distance between the subject's eye and the object. The simplified representation of the 3-D world was a cube. The 3-D Display System was used to display on a CRT the contact analog for the depth perception experiments.

CHAPTER 2

LINE BRIGHTNESS EXPERIMENTS

Two factors made intensity control necessary in the 3-D Display System. First, the CRT beam is held at the vertex of a triad during the time between drawing lines. This caused bright spots at the vertex points. Second, the lines are drawn in constant time periods. Originally all lines received the same amount of energy. This meant that short lines received more energy per unit length and were distractingly brighter than long lines.

The Tektronix 565 oscilloscope, with type P2 phosphor, has an input for intensity control. This input is A-C coupled to the intensity control grid. Since the RC time constant of the coupling network was small compared to the line drawing time, a sinusoidal input was chosen. By holding the input at zero while the CRT beam stands still and applying the sinusoidal signal while the beam is in motion, the bright spots at vertex points were eliminated. That is,

$$V = A \, sq(\omega_L t) \, \sin(\omega t)$$

where V is the voltage applied to the intensity input on the oscilloscope, A is the amplitude of the signal in volts, sq is a periodic function taking the values zero and one, ω_L is the line drawing frequency, and ω is the frequency of the sinusoid.

The sinusoidal intensity signal results in a sinusoidal intensity. The phase difference between intensity and the input is zero. The intensity control knob on the front of the oscilloscope is adjusted so that the intensity of the vertex points is just below the threshold of perception. Since the vertex points correspond to the portions of time when $sq(\omega_L t) = 0$, the sinusoidally intensified line is a dashed line. The input frequency controls dash length and number $(\frac{\omega}{2\omega_L})$ of dashes per line. It was found that $\omega = 60$ kHz, with $\omega_L = 360$ lines/second, made the dashes short enough and close enough together so that lines up to 5 cm long appeared solid.

The brightness of the dashes is a function of the amplitude of the sinusoidal intensity signal. This then is the means to make short lines the same brightness as long lines. The amplitude of the intensity signal must be less for short lines to eliminate their excessive brightness. That is,

$$V = A(L)\ sq(\omega_L t)\ \sin(\omega t)$$

where A(L) is the amplitude of the intensification signal as a function of the length of the line to be drawn, so that intensity is constant.

To determine the function A(L), an experiment, in which subjects adjusted A to make a variable length line the same apparent brightness as a reference line, was conducted. The 3-D Display System was modified to present two parallel horizontal lines. The time to draw a line and the frame time were not modified. One of the lines was of fixed length and intensified with a fixed amplitude signal. The other line was of variable length and intensified with an amplitude controlled by the subject. The computer selected the length of the variable line from a table. Presentation order was specified by a table of pseudo-random numbers. The amplitude chosen by the subject was stored by the computer. After the experiment, the computer printed the amplitudes chosen for each length and some statistical data. For a detailed explanation and listing of the intensity testing program, see Appendix C.

The presentation order was selected so that each line length occurred four times in the first half and four times in the second half. Ten line lengths, varying from 0.078 to 5.0 cm, were selected to be well separated on a log scale. The reference line was 5.0 cm long intensified with an amplitude of 9.0 volts. Both this reference level and the subject's adjustable level were multiplied by 3.5 sin(ωt), with ω = 60 kHz, to get the actual intensity signal. The time to draw each line was 2.8 milliseconds and each line was drawn 30.7 times per second. Reference and variable lines were separated by a vertical distance of 0.3125 cm.

The subject in the experiment was provided with a knob to adjust the intensity of the variable length line and a button to signal the computer that the adjustment was complete. The subject was presented with each of the ten line lengths eight times in pseudo-random sequence for a total of eighty trials. On the first forty trials he was asked to start from too bright and decrease intensity monotonically until the variable line and reference were of the same apparent brightness. On the second forty he was asked to increase intensity in the same fashion from too dim. The subject was asked to start the adjustment over if he felt that he had passed the correct value.

The experiment was run on ten subjects. The following statistics of the intensification signal amplitudes selected by each subject were computed for each line length: mean, standard deviation, maximum and minimum. The mean and standard deviation of the selected amplitudes was computed for the eighty responses (all subjects) at each length. The curve for the composite of all subjects is plotted on a linear scale in Figure 2.1 and on a log-log scale in the upper curve of Figure 2.2.

The standard deviation of the data for each line length was large compared to the difference in mean intensification amplitude between line lengths. To investigate the source of the variance, each subject was taken as perfect. That is, his ideal response was taken to be his mean with zero standard

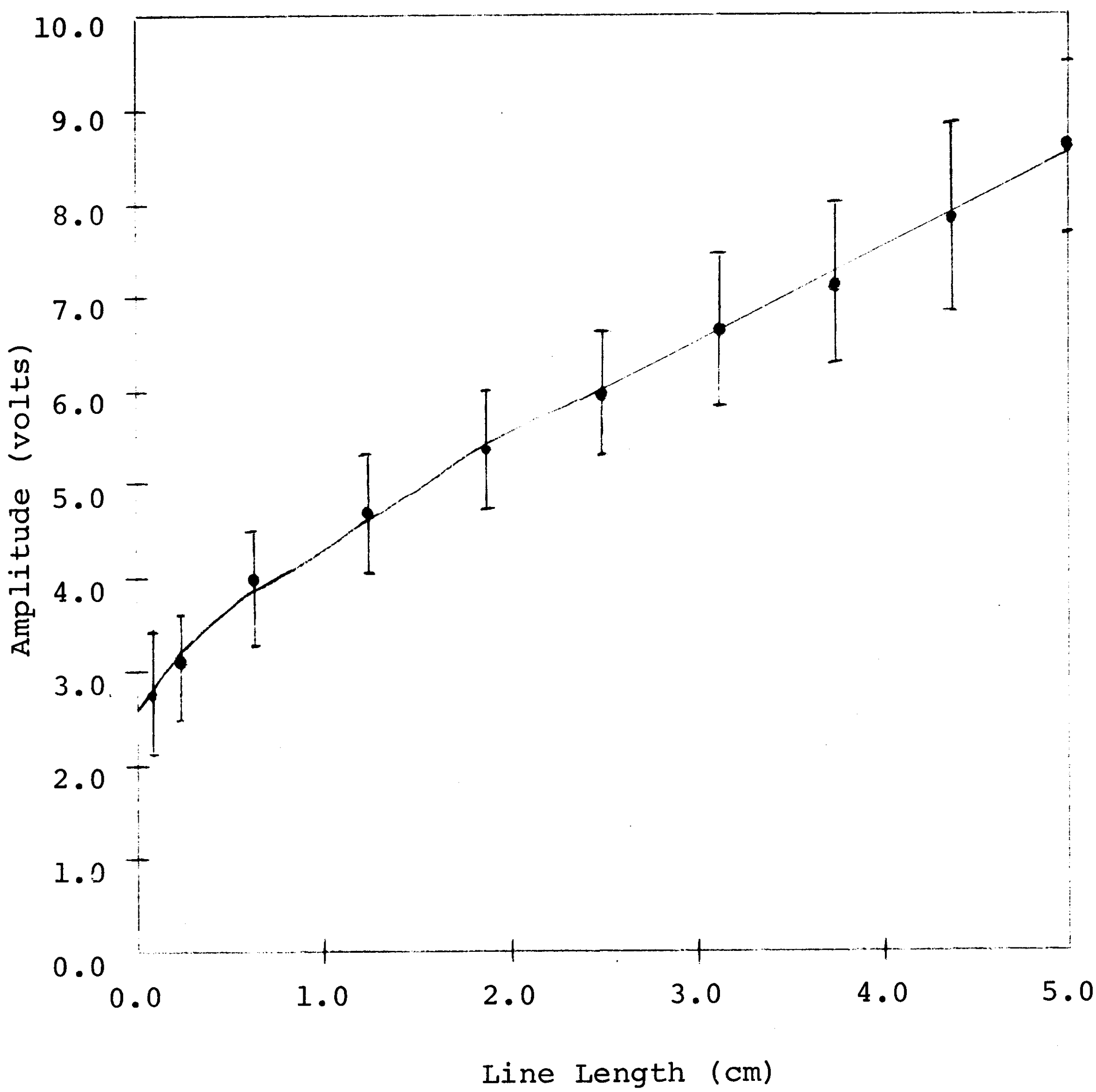


FIGURE 2.1 LINEAR PLOT OF INTENSIFICATION AMPLITUDE VERSUS LINE LENGTH

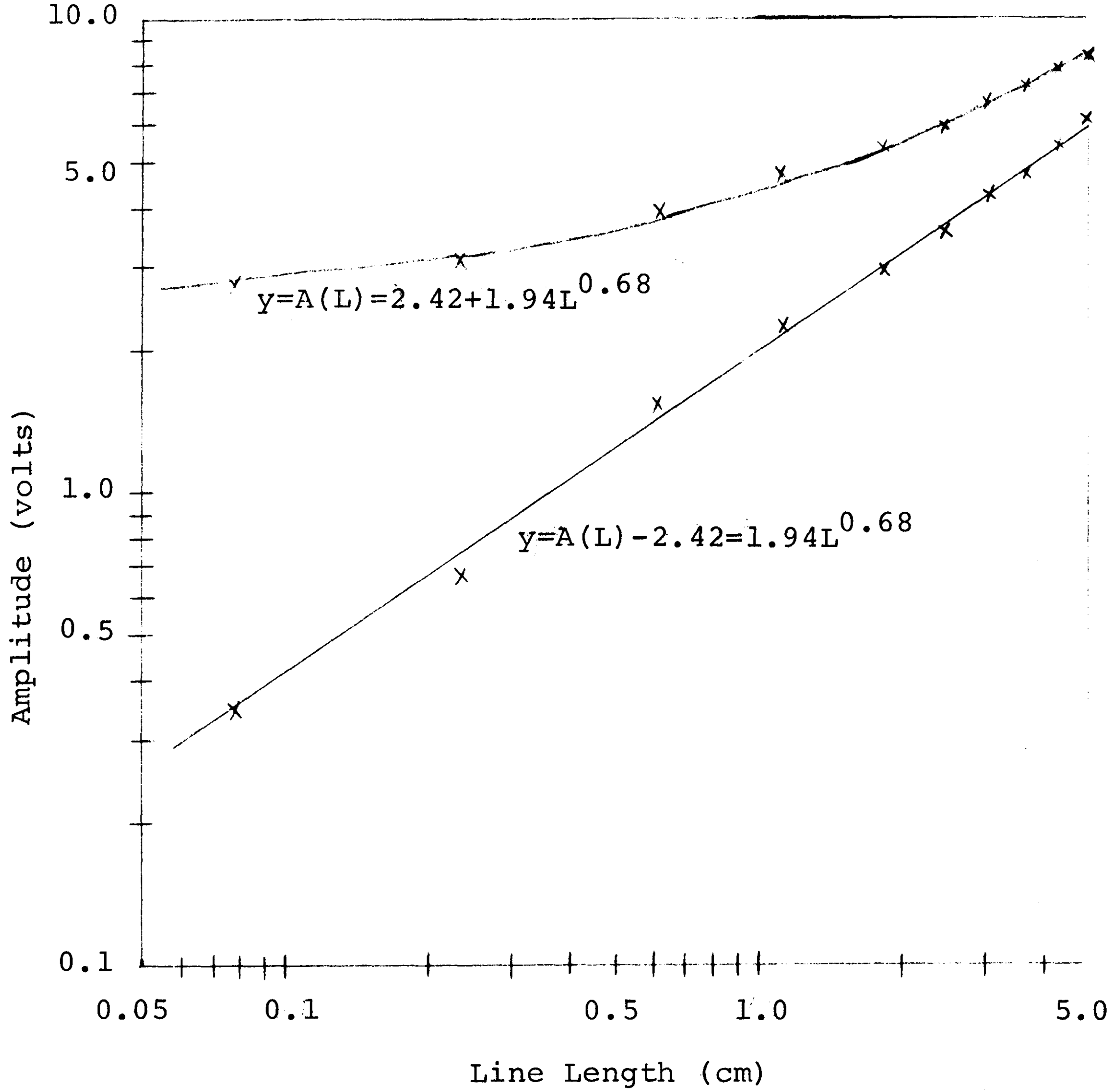


FIGURE 2.2 LOG-LOG PLOT OF INTENSIFICATION AMPLITUDE VERSUS LINE LENGTH

deviation. The standard deviation of the "perfect subject" means was 60 percent, or more, of the standard deviation of all data points. Thus, it is seen that more than half of the variability is from intersubject differences.

Using an A(L) which fit the means could convince all subjects that all line lengths were the same intensity because the variability of each subject was large. The composite mean was between the maximum and minimum amplitude for nine of the subjects on nine of the lines.

A function of the form

$$A(L) = C_1 + C_2 L^{C_3}$$

was fit to the means. If the constant C_1 is subtracted from each intensification amplitude, the data points fall on a straight line on a log-log plot. See the lower curve of Figure 2.2. A computer program was used to do a minimum mean square error log-log fit to determine C_2 and C_3. A parameter optimization technique to get the best minimum was used to find C_1. The resulting function is

$$A(L) = 2.42 + 1.94\ L^{0.68}$$

This is valid only for the particular CRT, phosphor, and brightness used in this experiment.

The 3-D Display System was modified to compute A(L) as given in the above equation. This was done using fast logarithm and antilogarithm subroutines. The subroutines operate in a fixed point system which works differently from the way logarithms are normally used on paper. For details of the logarithm subroutines used to find A(L) see Appendix A.

The display system with the implementation of A(L) was observed by many people. All agreed that the lines were of the same brightness regardless of length.

In reality an object such as is displayed would decrease in intensity as the inverse square of the distance from the object to the observer. In addition, at large distances, there is further reduction in intensity caused by the atmosphere. Thought was given to experimental procedures and equipment to measure this function, A(D), or the more generalized form, A(L,D). One experiment considered was asking a subject to adjust the intensity of one of two equal length lines to be one-half that of the other. This could have been done for a number of different line lengths and reference line intensities. This experiment was rejected because it is difficult for a subject to judge "half as bright." This experiment would produce data with large standard deviations and require a large body of data to get meaningful results.

The subject can do best at the task of adjusting two things to the same brightness. For this approach, an opaque cube with transparent blue edges and a light bulb inside would be used. With the cube placed at different distances from the subject, the subject could have adjusted the intensity of the displayed cube to be the same as the real cube.

This would have enabled direct measurement of A(L,D) without assuming the validity of the inverse square relationship between intensity and depth. Neither of these experiments was performed because of the time involved and because the exact form of the combined intensity function for length and depth was not pertinent to this thesis.

In order to test the effect of including intensity variation as a function of depth, the following form was implemented

$$A(L,D) = 2.42 + 1.94 \left(\frac{D_0}{D}\right)^{1.36} L^{0.68}$$

This form of amplitude as a function of line length and depth was arrived at based on the assumptions (1) that the phosphor had a linear characteristic between intensity and beam current, (2) that the additive constant was solely due to the fact that three times as much energy was going into a triad point as into a very short line, and (3) the exponent was a characteristic of the grid circuit, relating beam current to the intensity signal.

The display system was observed with this form of intensity variation. At greater distances, where the intensity was less, the short lines were brighter than the long lines. This suggests that the assumption (2), above, was incorrect. Apparently, the constant C_1 must also be multiplied by a function of D. In addition, the intensity seemed to decrease too rapidly with increasing depth. This suggests that assumption (1), above, was incorrect. Although this form was not correct, it allowed investigation of the improvement in depth perception given by intensity variation.*

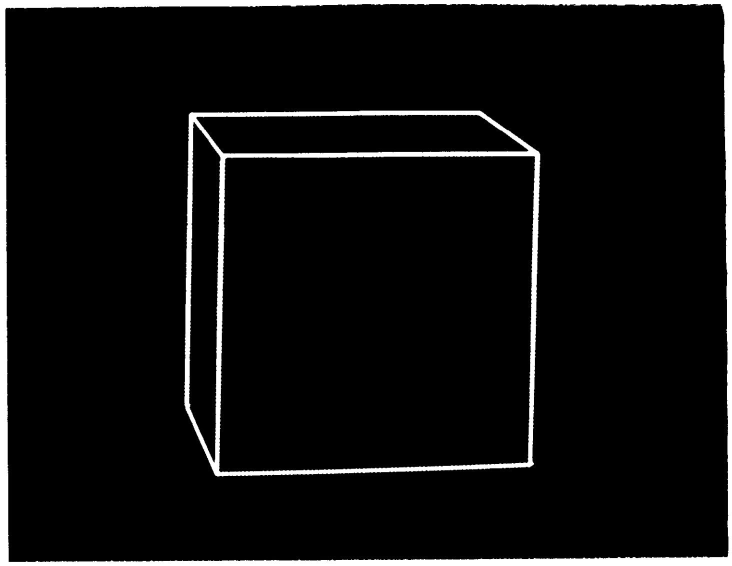
* See Appendix F

CHAPTER 3

THE EXPERIMENTS TO DETERMINE DEPTH PERCEPTION

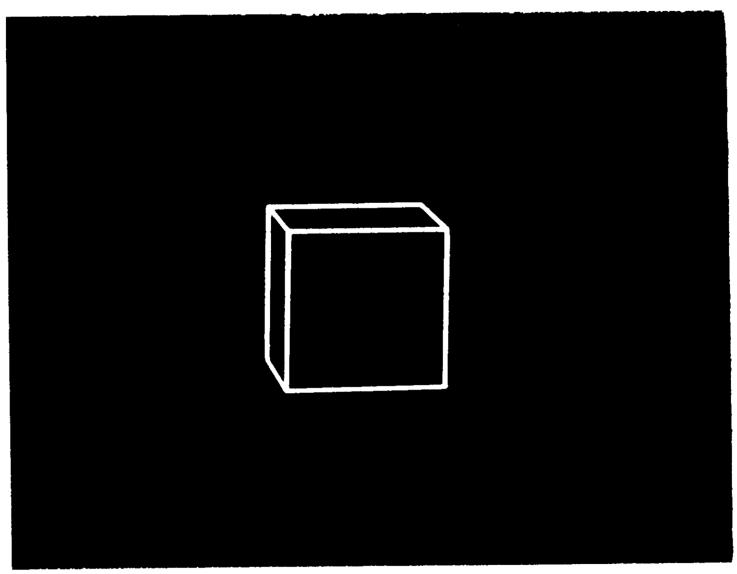
The 3-D Display System was modified for use as a test program to investigate depth perception from the display. The base line for comparison purposes was perspective for a fixed head position. Intensity variation with depth was added to the perspective information to find the amount of improvement from its addition. The M.I.T. Instrumentation Laboratory Head Position Monitor (see Appendix B) was used to measure the subject's lateral (left-right) head position. The computer used this measurement in the perspective equation to give the actual view from the subject's eye position. The improvement resulting from the addition of head movement was determined. The improvement from adding the combination of head motion and intensity was also determined.

The depth testing program presents a view of the cube at one of several fixed depths, some of which are shown in Figure 3.1. The subject's task is to identify which depth the cube is at. He signals his answer to the computer by pressing one of several buttons. The buttons are connected to multiple



5 cm

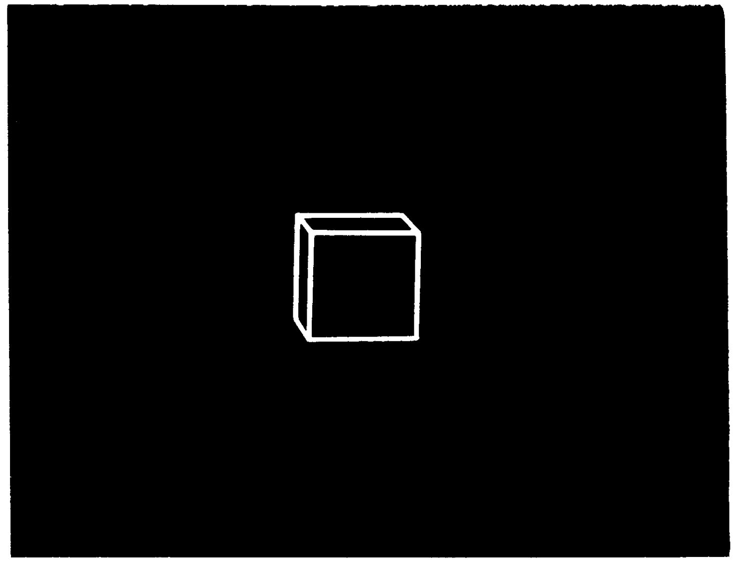
a) The Cube at 50 cm



5 cm

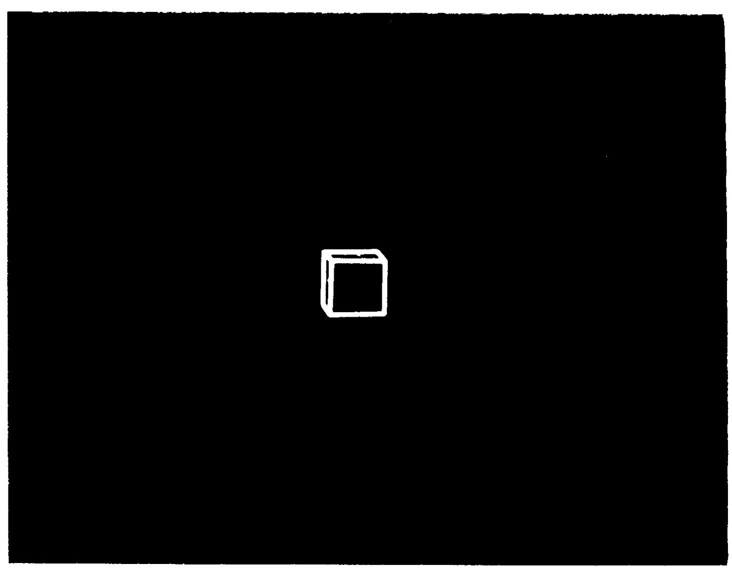
b) The Cube at 100 cm

FIGURE 3.1 THE 5-CM CUBE AT FOUR DEPTHS



5 cm

c) The Cube at 150 cm



5 cm

d) The Cube at 300 cm

FIGURE 3.1 (CONT.) THE 5-CM CUBE AT FOUR DEPTHS

OR gates which generate the binary number corresponding to the button.

The depth testing program automatically determines the next depth, presents the cube, and waits for and records the subject's response. The program takes a number from the presentation sequence table. This number specifies which entry in a table of depths is to be used. This depth constant is added to the appropriate coordinate of the points in the fixed inertial list and the result is stored in the variable inertial list of the 3-D Display System. Control is then transferred to the 3-D Display System, which computes the perspective view of the cube. The 3-D Display System is inhibited from updating the variable inertial list. As a result, the cube remains fixed in space. A switch is sensed to determine whether head position is to be fixed at zero or variable in the perspective equations. Constant or variable intensity is selected by changing two instructions in the display subroutine.

At the end of each frame the program checks to see if the subject has pushed a button. If not, the 3-D Display System continues displaying the cube. The depth program treats the button push in one of two ways depending on whether the presentation is for familiarization or experimental trials. During the familiarization, the button number and depth number are compared. If they are not equal, the display is continued. If they are equal, the next depth, in consecutive order, is presented. During the experimental trials the program presents the next depth, no matter which button was pushed. The depth program stores in matrix form the number of times that the j-th button was pushed in response to the i-th depth.

The program counts the number of presentations in the familiarization and halts before the experimental trials begin. The 100 experimental trials are then counted and the computer halts when the trials are complete. Finally, the stimulus-response matrix generated by the trials is printed and punched on paper tape. For the flow diagram and detailed description of the depth test program and button connections see Appendix D.

There was some problem with afterimages on the oscilloscope screen. This problem was reduced by installing a blue cellophane filter over the screen. With this filter, a two second delay between presentations was sufficient to make afterimage cues negligible. The oscilloscope had grid lines which could not be removed. The use of the filter made it impossible for the subject to see these grid lines, preventing him from measuring the image.

The subject was given twenty-two presentations in the familiarization series. First the closest, then the farthest were presented to give the subject the range of depths involved in the experimental trials. So that the subject could learn to identify each of the ten depths, they were first presented in consecutive order from closest to farthest, then in reverse order.

There were one hundred experimental trials with the ten depths being presented in pseudo-random order. The sequence was selected so that each of the ten depths was presented ten times. Each depth was followed once by each depth. That is, there was no correlation between the last depth and the present depth. These two criteria allowed uniform investigation of the stimulus-response matrix and prevented the subject from learning the sequence.

The cube was rotated slightly so that three sides could be seen. (See Figure 3.1.) It was centered on the oscilloscope screen and the depths were measured along the perpendicular to the screen. As a result, just apparent size changes, with no apparent translations, occurred as a result of the perspective transformation, without head movement.

The depths were selected on a logarithmic scale because the discrimination between depths, ΔD, is proportional to D. That is, the depths were selected to keep $\frac{\Delta D}{D}$ constant. The 3-D Display System was scaled for the distance, B, between the screen and the subject's eyes being 50 cm. With this scaling, the maximum distance of the 5-cm cube from the subject's eyes was about 315 cm. Three sets of depths were used in the experiments. One set spanned the whole available depth range from 53 to 301 cm, with $\frac{\Delta D}{D} = .213$, as given in Table 3.1. There was also a set of near depths, from 50 to 100 cm, as given in Table 3.2 and a set of far depths, from 150 to 300 cm, as given in Table 3.3, both with $\frac{\Delta D}{D} = .08$.

Depth Number	cm From Eye	Depth Number	cm From Eye
1	53.00	6	139.30
2	64.30	7	169.00
3	78.01	8	205.03
4	94.64	9	248.75
5	114.82	10	301.78

TABLE 3.1 FULL RANGE DEPTHS

Depth Number	cm From Eye	Depth Number	cm From Eye
1	50.15	6	73.47
2	54.00	7	79.34
3	58.32	8	85.69
4	62.99	9	92.55
5	68.02	10	99.95

TABLE 3.2 NEAR DEPTHS

Depth Number	cm From Eye	Depth Number	cm From Eye
1	150.00	6	220.40
2	162.00	7	238.03
3	174.96	8	257.07
4	188.96	9	277.64
5	204.07	10	299.85

TABLE 3.3 FAR DEPTHS

The set of depths from 53 to 301 cm was used for experiments on seven subjects. The conditions were perspective only, perspective with intensity variation, perspective with head movement, and perspective with head movement and intensity variation. In an attempt to minimize learning effects, the order was varied for different subjects. The experimental sessions were separated by at least one-half hour to avoid subject fatigue. The experimental order for each subject is presented in Table 3.4. The near and far depth sets were run with and without head movement. Four subjects were used. The experimental order for these subjects is given in Table 3.5. All head movements considered were one dimensional. The variable dimension was horizontal and parallel to the screen. Vertical head position was at the center of the screen.

The subject was told that the purpose of the experiments was to determine how well he could judge depth under different circumstances. It was explained that what he would see on the oscilloscope screen would be a display of a solid cube with lighted edges, in a dark room, seen through a window. In order to make the situation clear, he was given a chance to experiment with a cardboard mockup of the 10-cm window and a solid 5-cm cube in room light. The cube was placed at different distances and the size change effects of perspective were pointed out.

Subject	P	PI	PH	PHI
SV	2	4	3	1
GW	4	2	1	3
SB	1	2	3	4
LD	3	4	1	2
RV	1	2	3	4
MK	4	2	1	3
MG	2	1	4	3

P = Perspective only
PI = Perspective plus intensity variation
PH = Perspective with head movement
PHI = Perspective with head movement plus intensity variation

TABLE 3.4 EXPERIMENTAL ORDER FOR FULL DEPTH RANGE

Subject	N	NH	F	FH
SV	1	3	2	4
EG	3	1	4	2
GW	2	4	3	1
PM	4	2	1	3

N = Near depths without head movement
NH = Near depths with head movement
F = Far depths without head movement
FH = Far depths with head movement

TABLE 3.5 EXPERIMENTAL ORDER FOR SPLIT DEPTH RANGE

Then he was asked to move his head from side to side, and the change in view resulting from lateral head motion was pointed out. It was found that such a demonstration of the real world was necessary because the subjects were not familiar with looking through a window that small.

The subject was told that the closest depth was number one, and the farthest depth was number ten. The requirement that he press the correct button during familiarization insured that he knew the correct order. During the familiarization trials, the subject was asked to carefully examine the way the cube looked, so that he would be able to distinguish between them during the experimental trials. Each subject was offered the opportunity to repeat the familiarization if he thought that he could benefit from it.

During the experimental trials, the subject was asked to accurately identify the depth as quickly as possible and press the corresponding button. No time limit for his response was set.

CHAPTER 4

RESULTS OF THE DEPTH PERCEPTION EXPERIMENTS

The stimulus-response matrices resulting from the depth perception experiments were analized for information transmission and correlation. These techniques are described in Appendix E. The matrices for all subjects were added together for use in composite performance.

Briefly, information transmission is a measure of the effectiveness of a response in changing the prior probability of the stimulus. If the stimulus x_i is the presentation of the cube at the i-th depth and the response y_j is the selection of the j-th button, then the information transmission from x to y is given by

$$T(x,y) = \sum_i \sum_j P(x_i,y_j) \log \frac{P(x_i|y_j)}{P(x_i)}$$

where $P(x_i,y_j)$ is the joint probability of the stimulus-response pair, $P(x_i|y_j)$ is the posterior probability of the stimulus given the response, and $P(x_i)$ is the prior probability of the stimulus. For the case of experimental measurements the estimate of the information transmission is,

$$\hat{T}(x,y) = \sum_i \sum_j \frac{n_{ij}}{N} \log \frac{n_{ij}/n_i}{n_j/N}$$

where n_{ij} is the number of times the j-th button was selected in response to the i-th stimulus, n_i is the number of times the i-th stimulus was presented, n_j is the number of times the j-th button was selected, and N is the number of trials.

The results of the experiments for the full depth range are shown in Table 4.1. The performance measure entered is the information transmission, with the logarithms taken to the base 2. (Perfect transmission is $\log_2 10 = 3.322$.) Some subjects showed improvements as head motion and intensity were added and others' performance got worse. The performance of a subject closely follows the order in which he was tested on the various conditions. This is indicative that significant learning occurred for the perspective cue. Then, with a movable baseline, the results for an individual subject look either better or worse than the real improvements.

To the extent that each subject had the same learning behavior on the perspective cue, the effect of learning is eliminated from the composite results, because the experimental order was varied. The composite results are indicative of the improvement provided by the additional cues, but do not necessarily represent quantitatively accurate values. The composite results show that head movement is about twice as valuable a cue as intensity variation.

bject	P	PI	$\Delta\hat{T}$	%	PH	$\Delta\hat{T}$	%	PHI	$\Delta\hat{T}$
SV	2.65	2.61	-.04	-3	2.47	-.18	-12	2.42	-.23
GW	2.69	2.55	-.14	-9	2.69	0	0	2.65	-.04
SB	1.73	2.06	+.33	+26	2.25	+.52	+43	1.98	+.25
LD	2.54	2.41	-.13	-8.6	2.39	-.15	-10	2.23	-.31
RV	2.32	2.53	+.21	+16	3.11	+.69	+61	2.89	+.57
MK	2.49	2.04	-.45	-27	2.29	-.20	-13	2.15	-.34
MG	2.21	2.49	+.28	+21	2.82	+.61	+52	2.55	+.34
mposite	1.84	1.96	+.12	+8.7	2.05	+.21	+16	1.97	+.13

P = Perspective only
PI = Perspective with intensity variation
PH = Perspective with head movement
PHI = Perspective with head movement and intensity variation

TABLE 4.1 INFORMATION TRANSMISSION FOR FULL DEPTH RANGE

Both head motion and intensity variation showed improvements separately. But when both additional cues were combined, the improvement was more than for just intensity, but less than just head motions. Some subjects remarked during, or after, the experiment that it was more difficult to see the more distant cubes. This comment was given more often when head motion was included with intensity. It seems that the increased difficulty in seeing the cube prevented the subject from making full use of the cues resulting from head motion.

The results of the experiments for the split depth range are shown in Table 4.2. The performance measure entered is the information transmitted, with the logarithms taken to the base 2. The behavior of all subjects is quite similar, even though some had head movement first, and others had perspective only first. All subjects got more help from head movement in the 50-100 cm range than in the 150-300 cm range. It is seen that the improvement resulting from head movement drops off quickly as depth increases. The correlation coefficients for the composite are quite high. When the correlation is high, the correspondence between information and correlation is good. The level of confidence is .99, from analysis of the correlation coefficients, that the two near sets of data were produced from different joint probability distributions. The level of confidence for the far sets is .85. An additional twelve subjects would be needed to bring the confidence level for the far sets to .95. The additional subjects would at

Subject	N	NH	$\Delta\hat{T}$	%	F	FH	$\Delta\hat{T}$	%
SV	2.08	2.43	+.35	+27	1.88	2.03	+.15	+11
EG	1.39	1.79	+.40	+32	1.35	1.40	+.05	+3.5
GW	1.98	2.39	+.41	+33	1.58	1.86	+.28	+21
PM	1.80	2.32	+.52	+43	1.80	2.02	+.22	+16
Composite	1.42	1.91	+.49	+40	1.39	1.54	+.15	+11
Composite Correlation	.925	.964			.922	.941		

N = Depths from 50-100 cm without head movement
NH = Depths from 50-100 cm with head movement
F = Depths from 150-300 cm without head movement
FH = Depths from 150-300 cm with head movement

TABLE 4.2 INFORMATION TRANSMISSION FOR SPLIT DEPTH RANGE the same time reduce the uncertainty in the amount of improvement in the two cases.

The perspective equation for the lateral direction is

$$h = \frac{B}{D} y + (1 - \frac{B}{D})\ y_{hd}$$

where h is the horizontal screen coordinate, B is the distance from eye to screen, D is the depth, y is the lateral coordinate of the cube, and y_{hd} is the lateral head position. The influence, or "gain," of lateral head movement is $(1 - \frac{B}{D})$. Discrimination between depths depends on the depth derivative of this gain, $\frac{B}{D^2}$. Fitting a function of $\frac{B}{D^2}$ to the experimental data yielded that

$$\Delta T = \frac{B\ D_1}{1.22\ N} \sum_{n=1}^{N} \frac{1}{D_n^2}$$

where ΔT is the improvement in information transmission resulting from lateral head movement, B is the eye to screen distance, D_1 is the closest depth, D_n is the n-th depth in the set of N depths. The improvement in information transmission is the average of the derivatives at each depth, multiplied by the first depth in the set. Multiplication by D_1 constitutes an attention factor, or increased concentration on the head movement effects. (See the subject's subjective opinions given in the next paragraph and discussion in following paragraphs.) The constant essentially converts the improvement to the information measure. The calculated and measured improvements in information transmission are .15 and .15 respectively for the far depth set, .45 and .49 for the near depth set, and .236 and .21 for the full range depth set. Thus, the empirical formula fits the data to within about ten percent.

The subjective opinions of the subjects in the experiments were also sought. The general opinion was that the cube displayed never quite seemed to really be a cube in space. The subjects were always aware that it was an image on the oscilloscope screen. They did report, however, that the sense of reality was greater when the cube was near the screen. Some subjects felt that the larger apparent translations resulting from head movements, with the cube far behind the screen, were somewhat distracting. The subjects felt that head movement helped depth perception more at closer distances, and that head movement helped more than intensity variation.

The objective measurements agree well with the subject's opinions after the experiments. The biggest difference was in the worth of head movement at far distances. The comment about distraction came mostly on the full-range depth set. The wide range of head movement effects surprised the subjects who were not familiar with the real situation. The subjects were not aware that objects, that are far behind a window, move on the window just as the head moves. It was probably not the motions themselves, but the novelty of them, that was distracting.

The objective measurement did indicate improvement at far distances. Here any novelty wore off quickly because the subject attended closely to the phenomenon in an attempt to reliably distinguish the depths of the cube. With the full-range set of depths, the novelty wore off less quickly because the subject could more easily distinguish the perspective differences. This put him under less self-induced psychological pressure to attend to head movement phenomena.

The lack of reality is due to several reasons. The subject is brutally aware that he is looking at a picture on a CRT because the oscilloscope is in plain view. If a plain surface, large enough to fill his field of vision, had been placed to hide the oscilloscope except the actual screen, the oscilloscope may have been put far enough out of his consciousness so that the feeling of reality of the cube would have been greater. Another contribution to lack of reality was the location of the light bulb. The bulb was about six inches above the subject's eyes. This lever arm caused the bulb to move more than the eyes when the head was tilted. That is, the perspective changes were right for the location of the light bulb, but not for actual eye position. This separation between the eye and bulb was necessary because the bulb and socket were quite large. A smaller bulb with sufficient light output was not found. Also, the depth cues used were monocular cues. The subject used both eyes, but the effects of head movement seem most real if one eye is closed and the position of that eye accurately measured. Also, viewing an object without visible support (ground plane) or surrounding objects is quite unusual. Viewing an opaque cube with lighted edges, in the dark, would probably have produced similar feelings of unreality at the larger distances.

Head motion seems to help quantify depth perception by augmenting the perspective size change with linear position. That is, the displacement of the object is noted for a given head displacement. To some extent object velocity was noted relative to head velocity. The linear position helps most, because it is easier to estimate the distance of the object from the edge or center of the screen than to estimate size or velocity. In addition, velocity was less helpful because of the lag introduced in the head monitor to remove amplifier noise. At the nearer depths, the most frequent way that head movement was used, was to produce a fixed amount of rotation of the cube (line of sight parallel to left edge of cube) and note the translation of the cube. This was preferred to attempting to move the head a fixed amount.

The stimulus-response matrices for the composite of all subject are given in Table 4.3 to 4.10. The numbers entered are n_{ij}, the number of time the j-th button was selected in response to the i-th stimulus.

STIMULUS \ RESPONSE	1	2	3	4	5	6	7	8	9	10
1	52	14	1	3	0	0	0	0	0	0
2	0	43	19	5	3	0	0	0	0	0
3	0	1	32	28	4	2	3	0	0	0
4	0	0	3	34	23	7	3	0	0	0
5	0	0	3	6	29	24	6	2	0	0
6	0	0	0	1	11	32	20	5	1	0
7	0	0	0	0	0	10	38	18	4	0
8	0	0	0	0	0	1	6	49	9	5
9	0	0	0	0	0	0	0	8	50	12
10	0	0	0	0	0	0	0	0	12	58

TABLE 4.3 COMPOSITE STIMULUS-RESPONSE MATRIX FOR FULL RANGE DEPTHS WITH PERSPECTIVE ONLY

STIMULUS \ RESPONSE	1	2	3	4	5	6	7	8	9	10
1	56	13	0	1	0	0	0	0	0	0
2	0	38	21	10	1	0	0	0	0	0
3	0	1	38	22	6	3	0	0	0	0
4	0	0	5	35	22	6	2	0	0	0
5	0	0	1	7	31	24	7	0	0	0
6	0	0	0	0	6	35	27	2	0	0
7	0	0	0	0	1	9	33	27	0	0
8	0	0	0	0	0	0	12	41	17	0
9	0	0	0	0	0	0	0	11	55	4
10	0	0	0	0	0	0	0	0	13	57

TABLE 4.4 COMPOSITE STIMULUS-RESPONSE MATRIX FOR FULL RANGE DEPTHS WITH PERSPECTIVE AND INTENSITY VARIATION

	RESPONSE									
STIMULUS	1	2	3	4	5	6	7	8	9	10
1	57	10	1	2	0	0	0	0	0	0
2	0	47	16	6	1	0	0	0	0	0
3	0	0	47	11	11	1	0	0	0	0
4	0	0	1	43	20	6	0	0	0	0
5	0	0	0	6	35	20	9	0	0	0
6	0	0	0	0	4	35	28	3	0	0
7	0	0	0	0	0	6	37	25	2	0
8	0	0	0	0	0	1	5	45	19	0
9	0	0	0	0	0	0	0	9	49	12
10	0	0	0	0	0	0	0	0	13	57

TABLE 4.5 COMPOSITE STIMULUS-RESPONSE MATRIX FOR FULL RANGE DEPTHS WITH PERSPECTIVE AND HEAD MOVEMENT

	RESPONSE									
STIMULUS	1	2	3	4	5	6	7	8	9	10
1	53	13	4	0	0	0	0	0	0	0
2	0	37	25	7	1	0	0	0	0	0
3	0	3	27	23	17	0	0	0	0	0
4	0	0	1	29	26	13	1	0	0	0
5	0	0	0	2	34	29	5	0	0	0
6	0	0	0	0	4	25	36	5	0	0
7	0	0	0	0	0	0	38	31	1	0
8	0	0	0	0	0	0	5	33	32	0
9	0	0	0	0	0	0	0	7	47	16
10	0	0	0	0	0	0	0	0	18	52

TABLE 4.6 COMPOSITE STIMULUS-RESPONSE MATRIX FOR FULL RANGE DEPTHS WITH PERSPECTIVE, HEAD MOVEMENT AND INTENSITY VARIATION

	RESPONSE									
STIMULUS	1	2	3	4	5	6	7	8	9	10
1	25	13	1	1	0	0	0	0	0	0
2	14	17	8	1	0	0	0	0	0	0
3	1	13	16	10	0	0	0	0	0	0
4	0	3	22	4	10	1	0	0	0	0
5	0	0	5	15	17	3	0	0	0	0
6	0	1	1	7	12	14	4	1	0	0
7	0	0	0	0	14	8	16	2	0	0
8	0	0	0	0	3	14	8	13	2	0
9	0	0	0	0	1	3	13	16	7	0
10	0	0	0	0	0	0	9	11	15	5

TABLE 4.7 COMPOSITE STIMULUS-RESPONSE MATRIX
FOR DEPTHS FROM 50-100 CM
WITHOUT HEAD MOVEMENT

	RESPONSE									
STIMULUS	1	2	3	4	5	6	7	8	9	10
1	37	3	0	0	0	0	0	0	0	0
2	8	26	6	0	0	0	0	0	0	0
3	0	6	27	7	0	0	0	0	0	0
4	0	0	7	25	7	1	0	0	0	0
5	0	0	2	8	26	4	0	0	0	0
6	0	0	0	1	13	23	2	1	0	0
7	0	0	0	0	0	18	17	5	0	0
8	0	0	0	0	0	8	14	13	5	0
9	0	0	0	0	0	1	4	13	17	5
10	0	0	0	0	0	1	0	7	8	24

TABLE 4.8 COMPOSITE STIMULUS-RESPONSE MATRIX
FOR DEPTHS FROM 50-100 CM
WITH HEAD MOVEMENT

STIMULUS	RESPONSE 1	2	3	4	5	6	7	8	9	10
1	14	13	9	4	0	0	0	0	0	0
2	6	10	10	10	3	1	0	0	0	0
3	0	2	9	16	8	4	1	0	0	0
4	0	1	2	3	22	11	1	0	0	0
5	0	0	0	4	12	21	3	0	0	0
6	0	0	0	2	3	19	12	4	0	0
7	0	0	0	0	2	9	14	14	1	0
8	0	0	0	0	0	1	10	21	8	0
9	0	0	0	0	0	0	3	9	21	7
10	0	0	0	0	0	0	1	5	20	14

TABLE 4.9 COMPOSITE STIMULUS-RESPONSE MATRIX
FOR DEPTHS FROM 150-300 CM
WITHOUT HEAD MOVEMENT

STIMULUS	RESPONSE 1	2	3	4	5	6	7	8	9	10
1	10	18	9	3	0	0	0	0	0	0
2	3	14	13	7	2	1	0	0	0	0
3	1	1	9	18	11	0	0	0	0	0
4	0	1	1	11	17	10	0	0	0	0
5	0	0	1	4	13	18	4	0	0	0
6	0	0	0	0	6	16	14	4	0	0
7	0	0	0	0	1	4	17	17	1	0
8	0	0	0	0	0	2	9	16	13	0
9	0	0	0	0	0	0	2	8	21	9
10	0	0	0	0	0	0	0	3	8	29

TABLE 4.10 COMPOSITE STIMULUS-RESPONSE MATRIX
FOR DEPTHS FROM 150-300 CM
WITH HEAD MOVEMENT

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

It has been demonstrated that it is feasible to have a real time perspective display with little equipment added to a general purpose aircraft computer system. The present 3-D Display System runs at twenty-six frames per second and uses about eighty-five percent of our PDP-8 computer time. Since the PDP-8 has only a 12-bit word length and most guidance computers have a 36-bit word length, the time used on an aircraft system would be about one-third that on the PDP-8. This is because the computations for inertial updating are done in triple precision (36 bits) on the PDP-8. The display system may be integrated with other guidance and navigation functions, since it is processing strap-down inertial cutputs to keep track of the position of the inertially fixed object in the aircraft coordinate system. Certainly, digital readouts could be provided, as well as the displayed view through the window. The requirement of thirty percent of the digital computer time to run the 3-D display is quite reasonable.

The perspective cue from vehicle motions gives a good sense of the position of the vehicle in relation to the cube. A three axis control stick and a two axis control stick were used to give manual control over five of the six velocity inputs. With these controls it was possible for a "pilot" to "fly" the display. The pilot was able to fly the display as well as he was able to coordinate the five independent, uncoupled degrees of freedom. He had a good feeling for his position relative to the cube when directional ambiguities were removed by dotting three lines on the top face of the cube. (See Figure 1.1.)

Although the pilot had a good sense of relative depth, his feel for actual depth was not very good. In essence, the scaling of the problem was not clearly perceived. This was probably due to the perspective ambiguity between size and depth. That is, a small, near object may have the same apparent size as a large, distant object. This difficulty was further compounded by the expectations of the pilot. In general he expected velocities to be on the order of those of an aircraft. But since the cube was only 5 cm and the greatest depth was 315 cm, the velocity inputs were appropriately scaled down to make the display flyable. As a result, it was quite easy for the pilot to believe he was flying a fast display around a large cube which was far away. Even so, it was easy for him to understand the maneuvers that he was performing. The major problem with flying the display through a desired maneuver was the coordination of the five uncoupled velocity inputs to keep the cube within the pilot's field of view. The uncoupled velocity controls were used because they are the easiest dynamics for the untrained pilot to fly. Although translational velocities are sufficient to change position, the rotational velocities needed to be included so that the screen could be pointed toward the cube. Otherwise, it could not be seen at all times.

From the experimental results it is seen that the improvement in depth perception is quite good at distances under 1 meter. The improvement at 1.5 to 3 meters is only about one-third that at the closer range. Apparently, with a single object display, head motion would be advantageous for close maneuvering, such as in the final phases of docking. Other applications, where the objects are close enough for head movement to be valuable in aiding depth perception, are 3-D computer graphics and computer driven manipulators. But head movement is not worth the additional equipment for measuring it, in the cases of distant maneuvers, such as the approach and landing of an aircraft. Head movement is of little use at these large distances because the apparent translation of the cube is approximately equal to head translation and the apparent rotation of the cube is approximately zero. The perspective display without head movement is still valuable at these distances because the aircraft motions are orders of magnitude larger than head movements, and the pilot's head and the screen move with the vehicle. The larger apparent rotations of the cube and smaller apparent translations, resulting from vehicle motions, provide better depth information than the apparent rotations and translations produced by head movement, when the object is far away.

Head movements were tested only in the case of a single object. For displays with intermediate objects, the improvement from head movement will be better at large distances. As was noted in Chapter 4, the improvement from head motions is proportional to $\frac{B}{D^2}$. By comparing the motion of the target object to an intermediate object, the observer will effectively increase B to D_i, the distance of the intermediate object. The improvement, of course, requires that the position of the intermediate object be well-known. Even with intermediate objects, the best that might be achieved is discrimination proportional to depth. That is $\frac{\Delta D}{D}$ is a constant. It is clear that additional objects, that are far behind the target object, will not appreciably improve depth perception.

The human observer is able to quantify intensity much less well than position. Its value as a cue is less than head movement at all depths. Better use of intensity cues with greater familiarity, or more learning, is not as likely as with head movements. As was pointed out in Chapter 4, with large intensity changes, the dimness of distant objects makes it more difficult to use head movement cues. If the intensity changes less with depth, such as $\frac{1}{D}$, then it does not provide as much additional information because of the relatively poor intensity discrimination. If the intensity is used in some way other than a straightforward monotonic way, more improvement might be realized. For example, the intensity could be made cyclic with the hope of subdividing the perspective discrimination interval. But it is very doubtful that this approach would help much, because such a display would not be as natural and easy to use, and as a result, require more learning than a straightforward display. It seems that intensity variation is not the most promising cue to improve depth perception from a 3-D display.

The most promising approach seems to be a perspective display with several objects between the aircraft and the target object. Here the change in field of view also helps depth perception and the sensation of reality. That is, head movement, in addition to producing apparent rotations and translations of the objects already in the field of view, moves new objects into the field of view. Thus there are additional cues here which need experimental evaluation.

Although multiple object displays were not investigated in this thesis, several things indicate their superior value. If one looks out from the rooftop of a tall, isolated building, he has a good sense of being up high, but it is not very quantitative. But when he looks straight down over the edge, he sees all the intermediate window ledges and has a much stronger sense of elevation, and a much better quantitative idea of that height. In the driving situation, the combination of trees, telephone poles, and passing lines greatly improve depth perception.

Essentially, the observer can count the intermediate objects and, knowing the distance between objects, more easily and accurately determine the distance to the target object. There are three ways of counting. The first is enumeration which works for any number of objects, but is relatively slow. The second is guessing, which is faster but less accurate. The third is subitizing, in which the number of objects, up to about seven is accurately and reliably perceived almost instantaneously. As a result, there is an optimum number of intermediate objects. Thus the depth perception problem is reduced to estimating the distance to the first intermediate object and counting the total number of intermediate objects.

The simplest intermediate objects are straight lines. For the aircraft display problem, then, the desired flight path could be presented as a series of straight lines in perspective. For a simple straight-in flight path the series of lines, or "object," would be similar to the one in Figure 5.1. In addition to providing better depth information, the series of horizontal lines provide better altitude information. The verticals help crosstrack information. This type of display is more valuable as the approach path

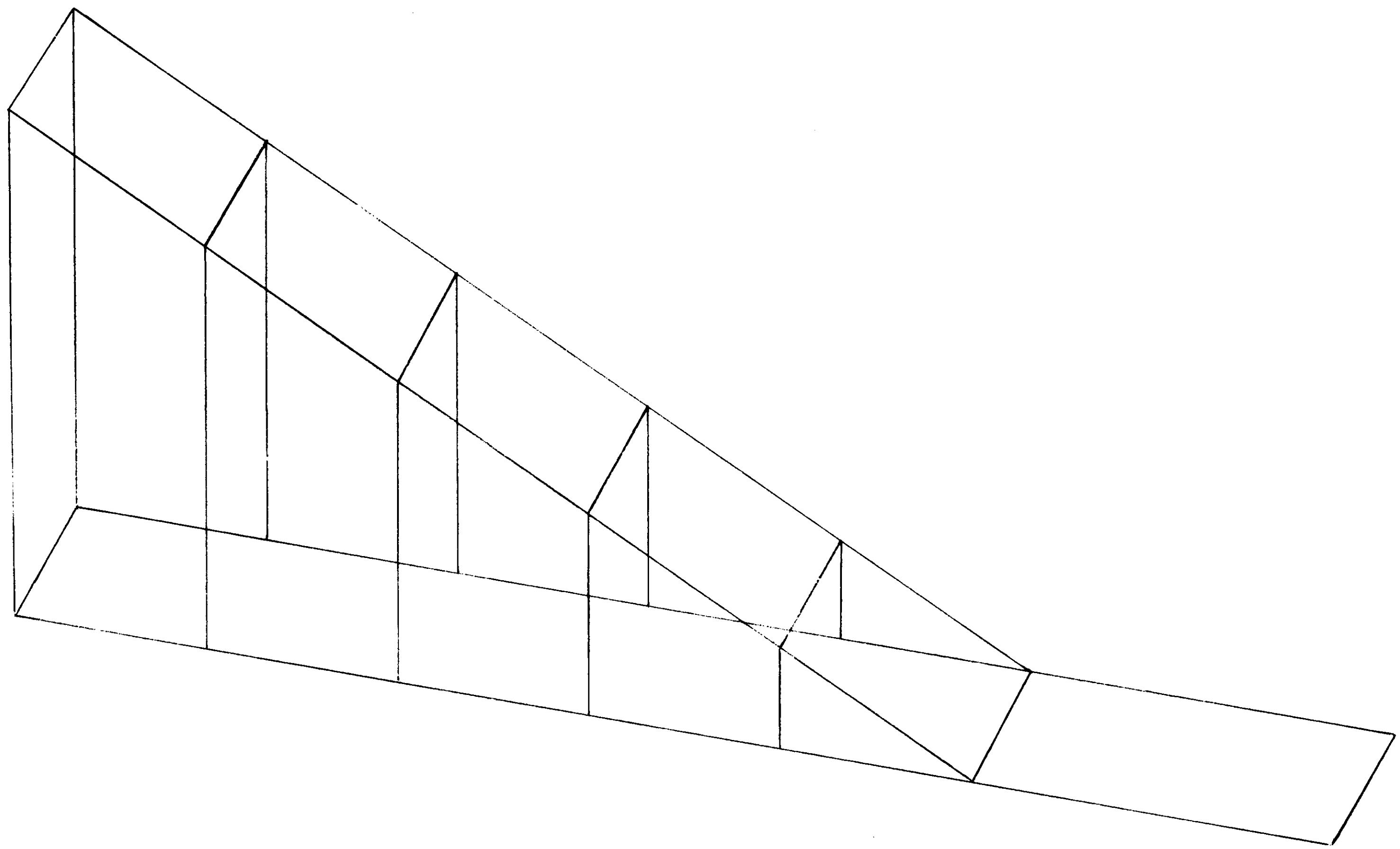


FIGURE 5.1 PROPOSED OBJECT FOR FLIGHT PATH DISPLAY

becomes more complex, that is, descent in stages, and/or turns are required. This display has the added advantage that it "predicts," or shows in advance, the guidance input.

APPENDIX A

THE 3-D DISPLAY SYSTEM

The 3-D Display System keeps track of the points of an inertially fixed cube in a coordinate system fixed to the vehicle. The coordinate system used is shown in Figure A.1. These points are transformed by the equations of linear perspective with head motion. The points that are hidden by the volume of the cube are tagged for blanking. The intensification signal amplitude is computed as a function of line length and depth. The edge lines that are seen are displayed on an oscilloscope. The translation and rotation rates of the vehicle, and lateral head position, all as measured in the coordinate system fixed to the vehicle, are inputted to the 3-D Display System via analog to digital conversion.

The equations used to rotate vectors must not increase the length of a vector as it rotates. One way to satisfy this requirement is using serial set of equations. In a planar case the replacement equations are

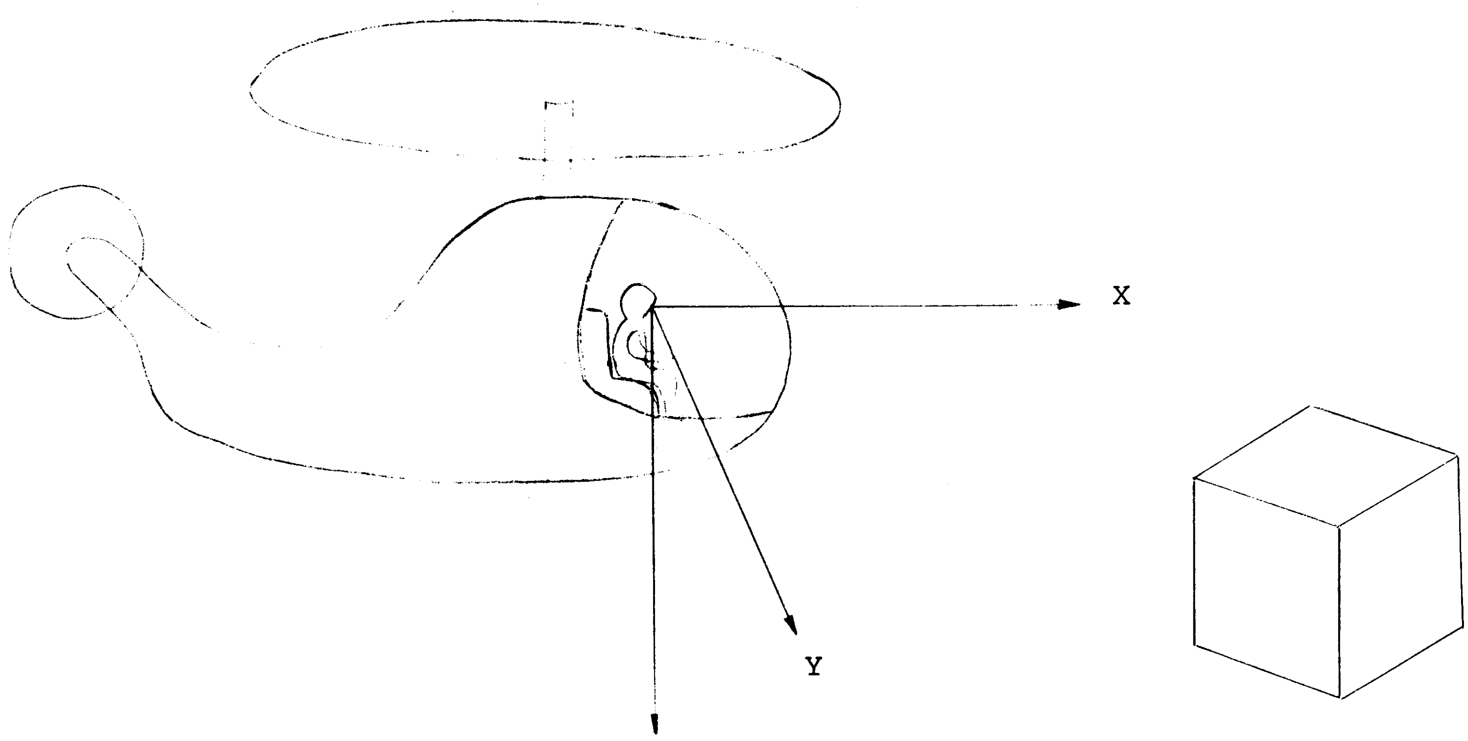


FIGURE A.1 COORDINATE SYSTEM FIXED TO THE VEHICLE

$$x \leftarrow x + y\ \Delta\psi$$

$$y \leftarrow y - x\ \Delta\psi$$

where x and y are the components of the vector and $\Delta\psi$ is the incremental rotation angle.

A further requirement is that a positive sense rotation followed by a negative sense rotation of equal magnitude brings the vector back to its original position with no length change. One way to satisfy this requirement is to use an alternating-order, serial set of equations. In a planar case the replacement equations are

$$x \leftarrow x + y\ \Delta\psi$$

$$y \leftarrow y - x\ \Delta\psi$$

$$y \leftarrow y - x\ \Delta\psi$$

$$x \leftarrow x + y\ \Delta\psi$$

For full three dimensional rotations, the final orientation of the vector is approximately independent of the order in which the rotations are applied, if the rotations are small, incremental angles. Performing a set of three incremental rotations each update cycle is equivalent to rotating the vector with the corresponding components of angular rate. This brings in the dynamical requirement that a vector having been rotated by applying agiven time history of rotation from 0 to T,

$$\Delta\theta = f_1(t) \qquad 0<t<T$$

$$\Delta\phi = f_2(t) \qquad 0<t<T$$

$$\Delta\psi = f_3(t) \qquad 0<t<T$$

will be brought back along the same path to the original position by applying the same rotational history reversed in sign and time

$$\Delta\theta = -f_1(T-t) \quad 0<t<T$$

$$\Delta\phi = -f_2(T-t) \quad 0<t<T$$

$$\Delta\psi = -f_3(T-t) \quad 0<t<T$$

There is a similar dynamical requirement when combining translations with the rotations. One way to satisfy these dynamical requirements is to make the order of the serial updating equations symmetric. That is, the rotations are done in the order ϕ, θ, ψ, ψ, θ, ϕ and translations are combined with rotations in the order translate, rotate, translate in each cycle. The full set of replacement equations, to perform the three dimensional translations and rotations in the coordinate system fixed to the vehicle, as implemented in the 3-D Display System, are

$$x \leftarrow x + \Delta x$$

$$y \leftarrow y + \Delta y$$

$$z \leftarrow z + \Delta z$$

$$y \leftarrow y + z\ \Delta\phi$$

$$z \leftarrow z - y\ \Delta\phi$$

$$z \leftarrow z + x\ \Delta\theta$$

$$x \leftarrow x - z\,\Delta\theta$$

$$x \leftarrow x + y\,\Delta\psi$$

$$y \leftarrow y - 2\,x\,\Delta\psi$$

$$x \leftarrow x + y\,\Delta\psi$$

$$x \leftarrow x - z\,\Delta\theta$$

$$z \leftarrow z + x\,\Delta\theta$$

$$z \leftarrow z - y\,\Delta\phi$$

$$y \leftarrow y + z\,\Delta\phi$$

$$x \leftarrow x + \Delta x$$

$$y \leftarrow y + \Delta y$$

$$z \leftarrow z + \Delta z$$

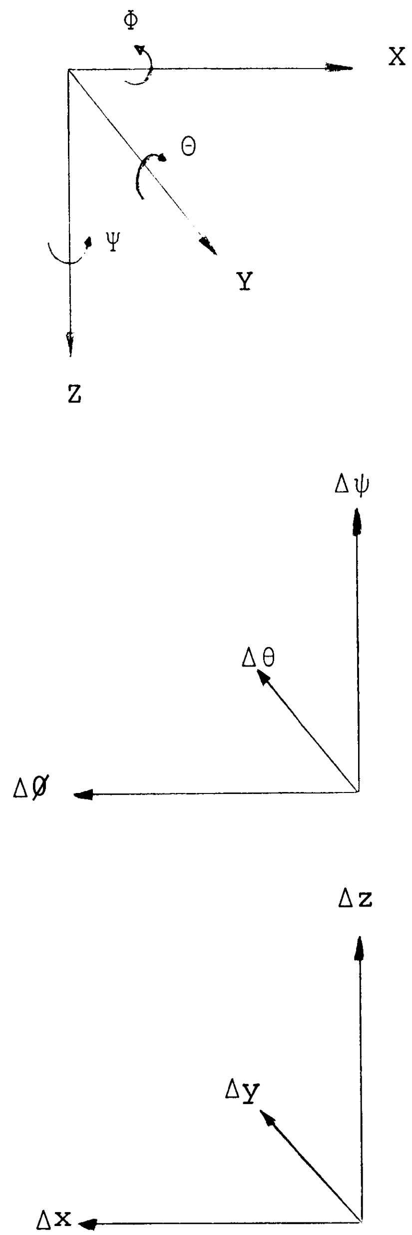
where x, y, and z are the coordinates of the point of the cube; Δx, Δy, and Δz are the incremental translations; and $\Delta\phi$, $\Delta\theta$, and $\Delta\psi$ are the incremental rotations as shown in Figure A.2.

The perspective equations, as implemented in the 3-D Display System, are

$$h = \frac{B}{x}(y - y_{hd}) + y_{hd}$$

$$v = -\frac{B}{x}z$$

where x, y, and z are the coordinates of the point of the cube, B is the eye to screen distance, y_{hd} is the lateral head position, and h and v are the horizontal and vertical screen coordinates as shown in Figure A.3.



a) Coordinate System Fixed to the Vehicle

b) Corresponding Vector Directions of Positive Incremental Rotations

c) Corresponding Vector Directions of Positive Incremental Translations

FIGURE A.2 THE COORDINATE SYSTEM FIXED TO THE VEHICLE AND THE DIRECTIONS OF INCREMENTAL INPUTS

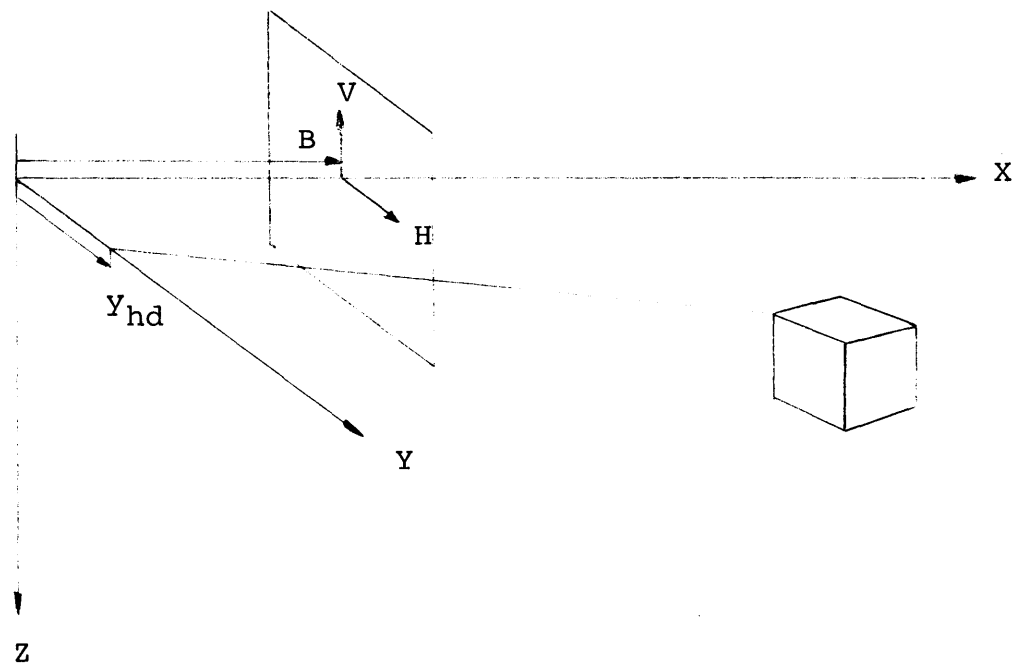


FIGURE A.3 THE SCREEN COORDINATE SYSTEM RELATIVE TO THE VEHICLE COORDINATE SYSTEM

Blanking of the lines hidden by the volume of the cube is accomplished in several steps. First, the dot product between the vector from the eye to a point on the side and the inward pointing vector normal to the side is computed. See Figure A.4. Then if the dot product is negative, the side is not seen. If, and only if, all three sides that intersect in a point are not seen, then that point is not seen. Finally, if one, the other, or both end points of an edge are not seen, then the entire edge is hidden.

The dot product computation makes use of the facts that (1) an edge is normal to a side for a cube, (2) the vector from the eye to the point is the vector from the origin to the point minus the vector from the origin to the eye, and (3) the sign of the dot product is independent of the magnitudes of the vectors. The lines of sight to two points of the cube and the three edges at those two points give the information for all six sides.

For the computation of the intensity signal amplitude as a function of line length and object depth, A(L,D), fixed point logarithm and antilogarithm subroutines are used. Fixed point logs require that the location of the binary point be taken into consideration so that unity raised to any power is unity. For the equation

$$F^d = x^a \, y^b \, z^c$$

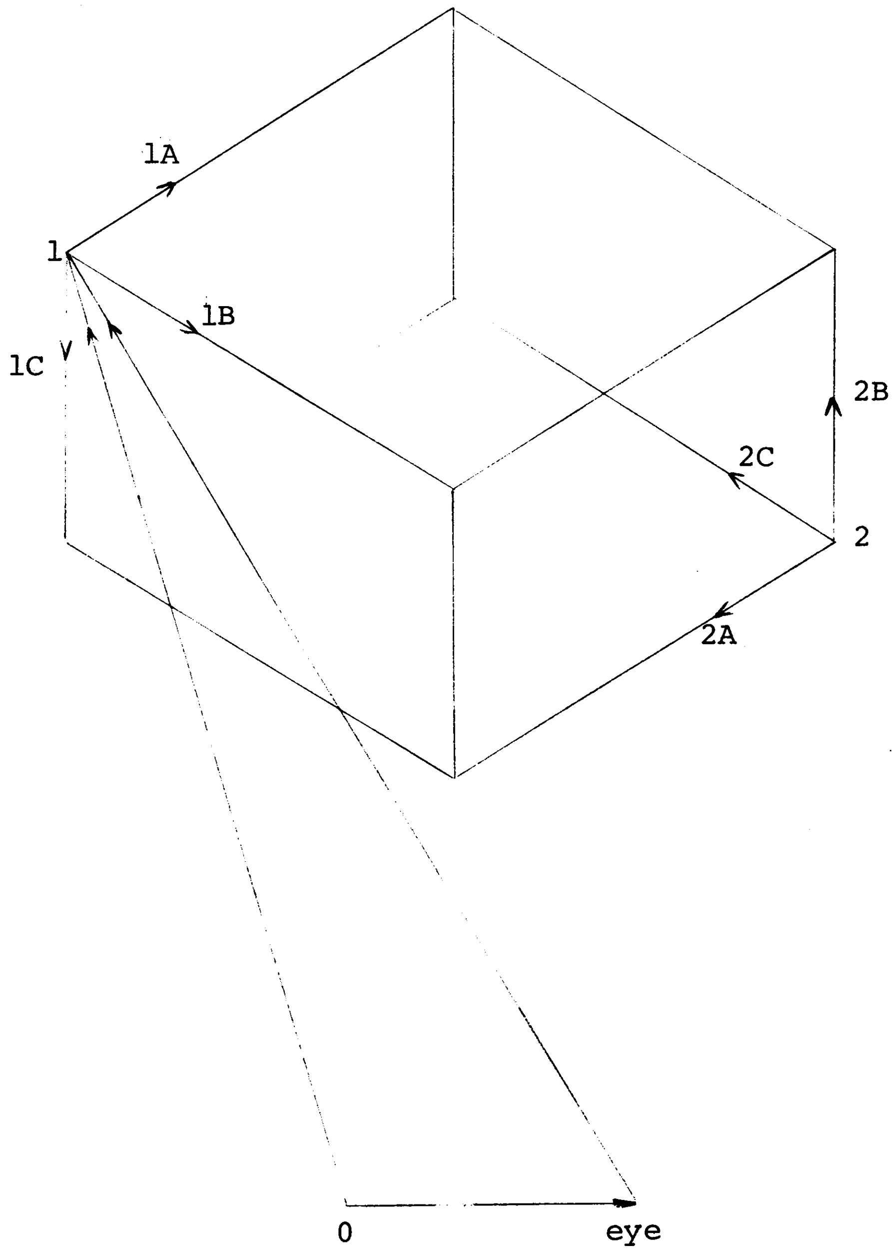


FIGURE A.4 THE VECTORS USED TO DETERMINE HIDDEN LINES use of fixed point logs yields

$$d \log F = a \log x - a \log 1_x + b \log y - b \log 1_y$$
$$+ c \log z - c \log 1_z + d \log 1_f$$

where, 1_x is the octal representation of unity for the variable x, that is

$$1_x \, 1_x = 1_x$$

Applying this to the intensity signal amplitude

$$A(L,D) = 2.42 + 1.94 \left(\frac{D_0}{D}\right)^{1.36} L^{0.68}$$

Let

$$P = 1.94 \left(\frac{D_0}{D}\right)^{1.36} L^{0.68}$$

The actual quantities inputted to the computation are D^2 and L^2. Thus, taking the log of both sides and converting the constants to their octal equivalent

$$\log P = \log 2 + 5253_8 \log D_0^2 - 5253_8 \log 1_{D_0^2}$$
$$- 5253_8 \log D^2 + 5253_8 \log 1_{D^2}$$
$$+ 2525_8 \log L^2 - 2525_8 \log 1_{L^2} + \log 1_P$$

For the 3-D Display System, the scaling of variables is

$$1_{D_0^2} = 1_{D^2}$$

$$1_{L^2} = 12_8 \qquad (cm^2)$$

$$1_P = 315_8 \qquad (volts)$$

The sum of the constant terms is (with $D_0 = 300_8$) *

$$\log 2 + 5253_8 \log D_0^2 - 2525_8 \log 12_8 + \log 315_8 =$$

$$525_8 + 1631_8 - 576_8 + 5075_8 = 6655_8$$

The simplified result is

$$\log P = 2525_8 \log L^2 - 5253_8 \log D^2 + 6655_8$$

and finally

$$A(L,D) = 600_8 + \text{alog}\ (2525_8 \log L^2 - 5253_8 \log D^2 + 6655_8)$$

For constant intensity

$$A(L) = 600_8 + \text{alog}\ (2525_8 \log L^2 + 5024_8)$$

The cube is drawn as a set of four "triads," as shown in Figure A.5, in order to minimize data transfers from the digital computer to the display. Each line is drawn on the oscilloscope screen using horizontal and vertical deflection voltages that are linear parametric functions of time. The deflection voltages are generated using analog components. The coordinates, (h,v), of the triad vertex are applied to integrators operating in a track and hold fashion. The Δh

* See Appendix F

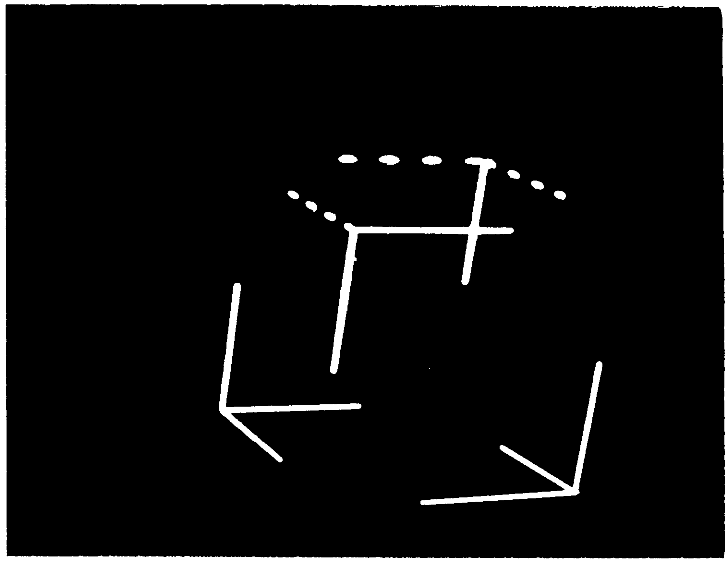
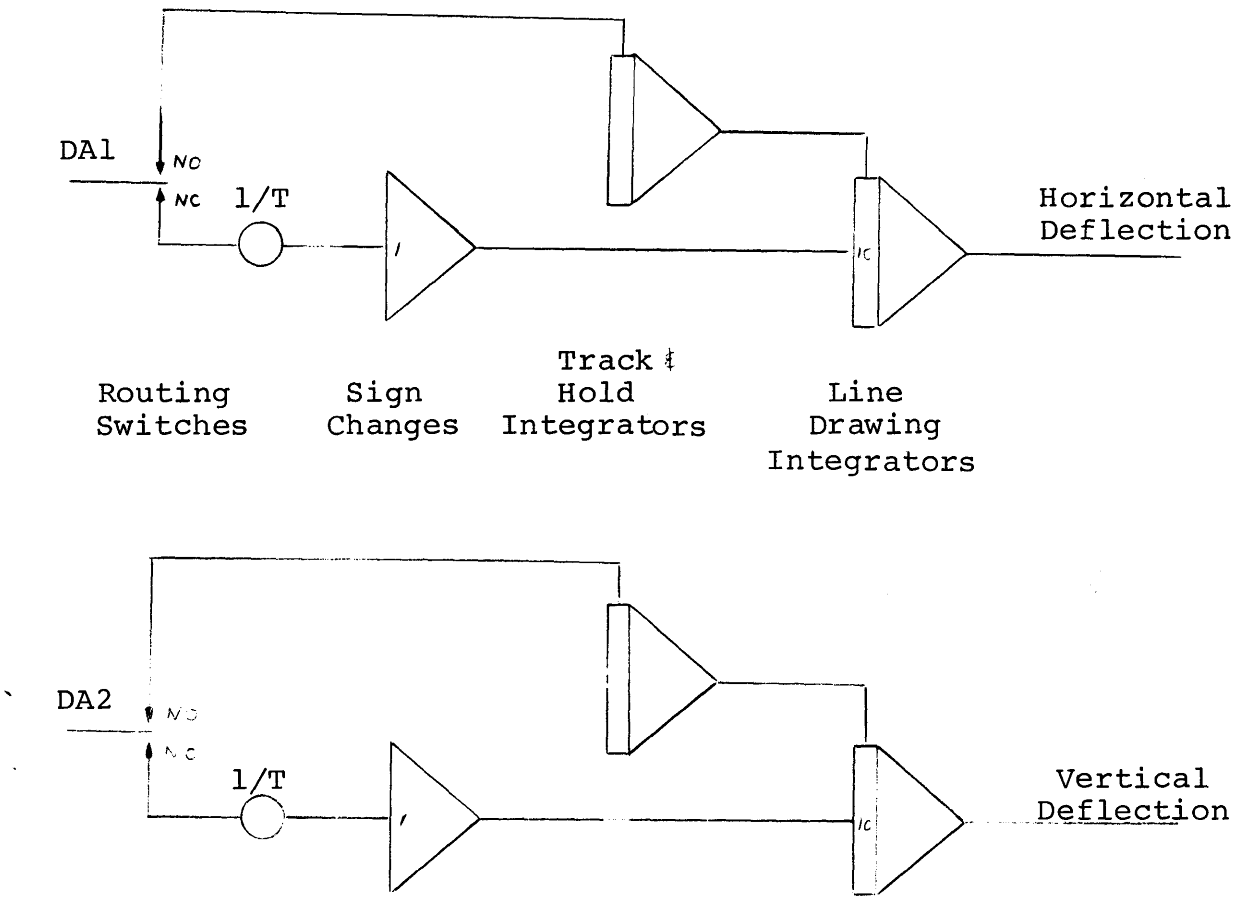


FIGURE A.5 THE CUBE AS A SET OF FOUR TRIADS and Δv for each of the three lines of the triad are sequentially applied with a gain of $1/T$ to the inputs of two line drawing integrators and integrated for T seconds from initial conditions h and v. The integration time T is 3.2 milliseconds. Dotted lines are produced by reducing the frequency of the intensification signal. (See Chapter 2.) The analog patch board interconnections are shown schematically in Figure A.6.

The display is free running under the control of a logic circuit on the control patch board. This controls the mode (initial condition or compute) of the holding and line drawing integrators, position of electronic switches for h-Δh routing, blanking, line dotting, and sine wave synchronization for the intensity signal, and generates program interrupts to request display data transfers. The logic symbols are defined in Figure A.7 and the control patch board interconnections are shown schematically in Figure A.8. The signals at the lettered points of Figure A.8 are shown in Figure A.9.

Control line 1 is used for timing information. It is at -3 volts when the digital program is waiting for frame synchronization. Control lines 2 and 3 are unused. Control line 4 is used for line dotting. It is at -3 volts when the line is to be dotted. Control line 5 is used for blanking based on the vertex end point of a line. It is at ground to blank the line. Control line 6 is used for blanking based



LINE DRAWING SECTION

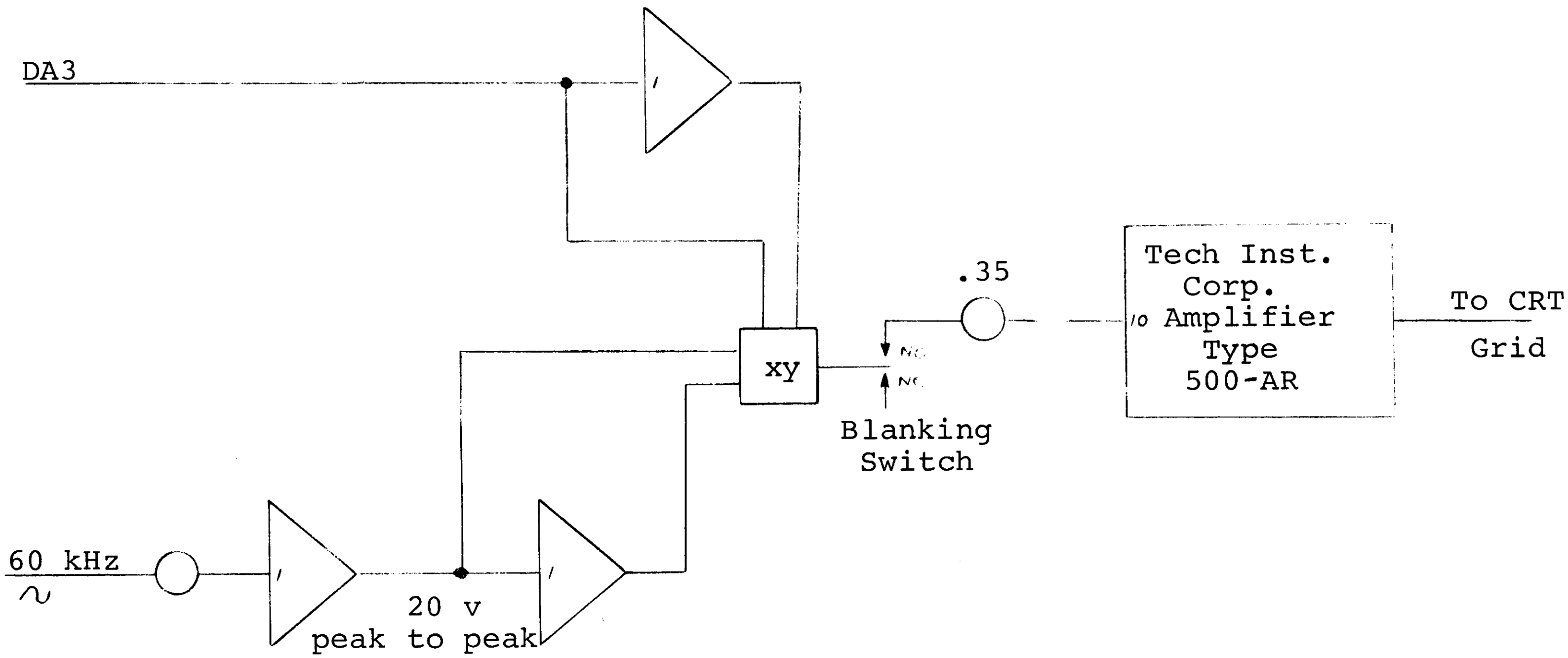
All integrators are on Rate 100

Synchronization is $\overline{A}$

A clock = 1500 μsec

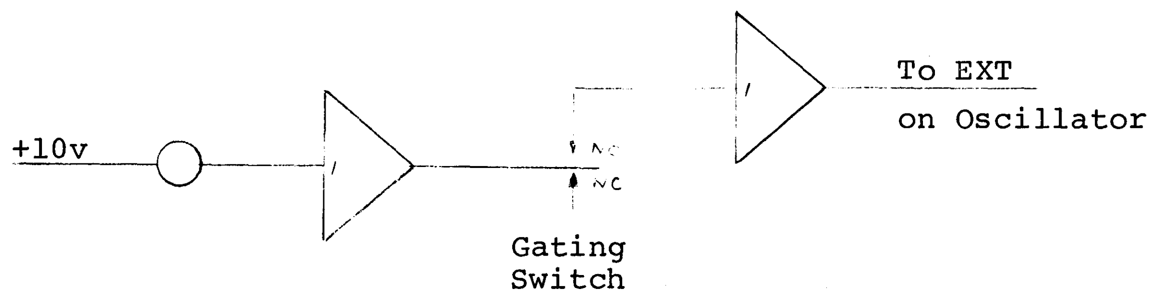
$\overline{A}$ clock = 100 μsec

FIGURE A.6 ANALOG PATCH BOARD INTERCONNECTIONS

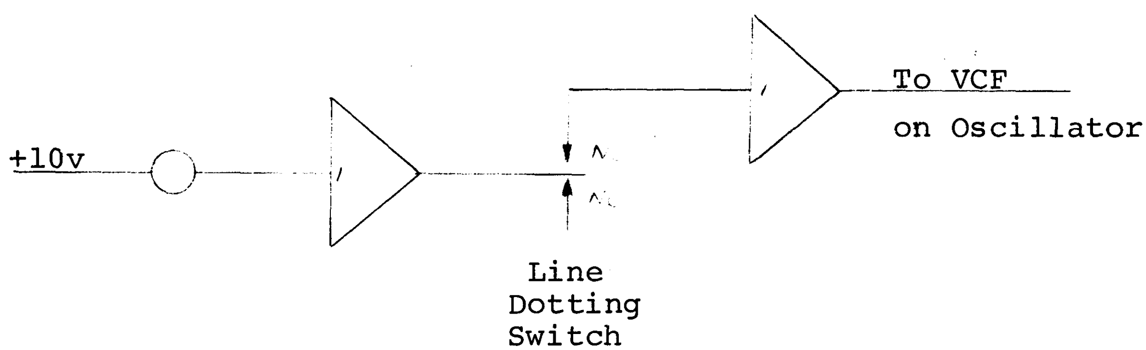


Intensification Circuit

FIGURE A.6 (CONT.) ANALOG PATCH BOARD INTERCONNECTIONS



Synchronization to Hold Dots Steady



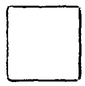
Line Dotting Circuit

MODE selector on GATE

VCF Control to MAX

FIGURE A.6 (CONT.) ANALOG PATCH BOARD INTERCONNECTIONS

Symbol	Name	In-Out Table

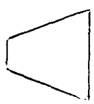


Inverter

In	Out
-3	GND
GND	-3

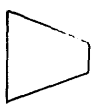
NAND

In		Out
-3	-3	GND
GND	-3	-3
-3	GND	-3
GND	GND	-3



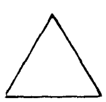
Output
Converter

In	Out
-3	+6
GND	GND



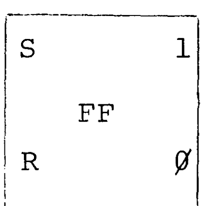
Input
Converter

In	Out
+6	-3
GND	GND

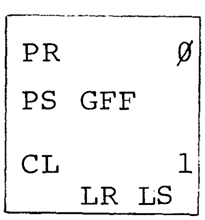


Schmitt
Trigger

Ground Pulse Out
on input transition
from GND to -3



Set-Reset Flip-Flop



Gated Flip-Flop (Divide by Two)
LR LS are GND to enable the Gates

FIGURE A.7 LOGIC SYMBOL DEFINITION

-3 v	=	logical 1
GND	=	logical Ø
ESn	=	electronic switch n
CLn	=	output of control line n
SLn	=	input to sense line n
EMC	=	the electronic mode control for an integrator
BLn	=	button bit line n
POT SET	=	+6 v if POT SET indicator light is on
A Clock	=	6 v synchronized A clock direct output

FIGURE A.7 (CONT.) LOGIC SYMBOL DEFINITION

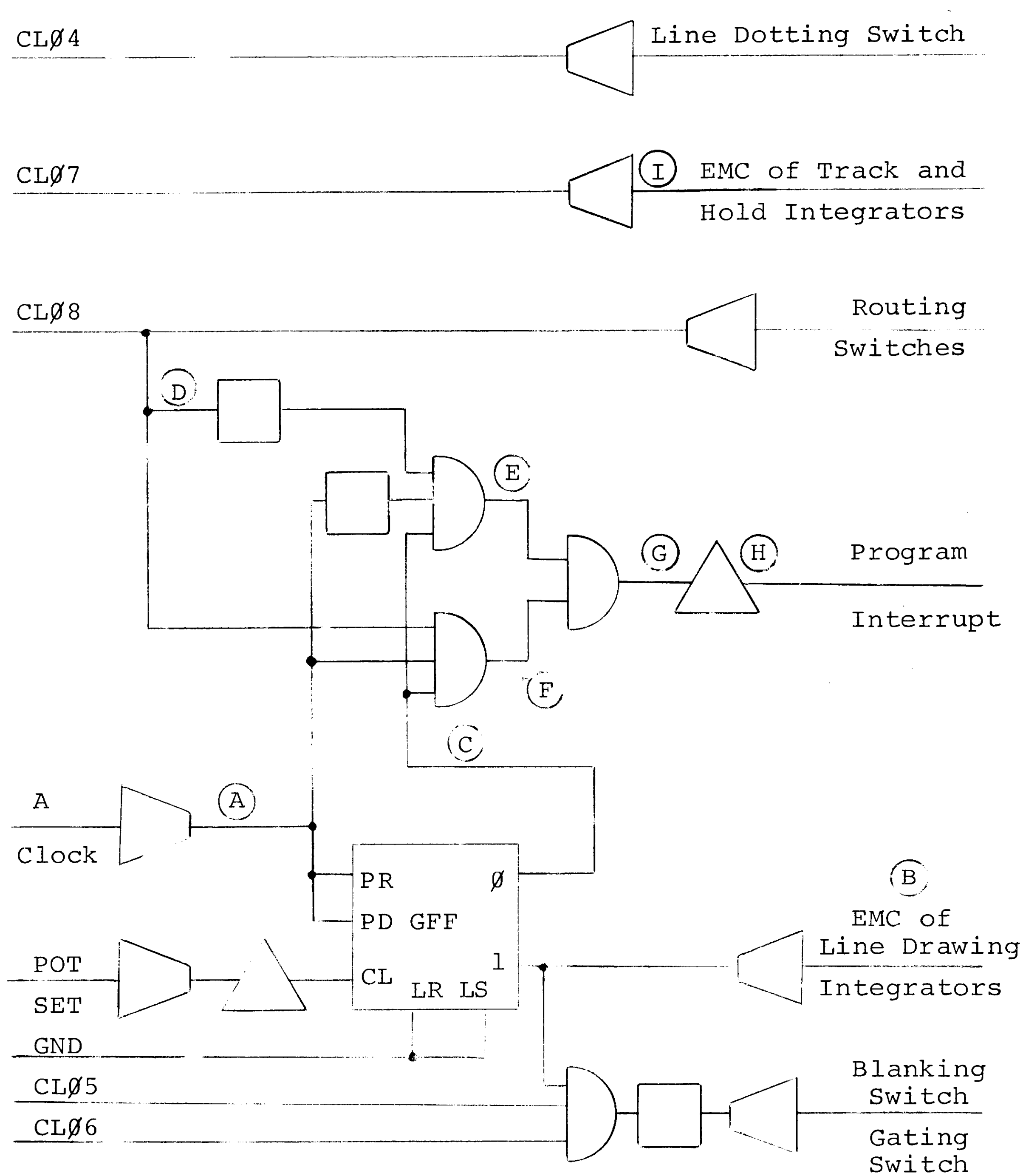


FIGURE A.8 CONTROL BOARD INTERCONNECTIONS

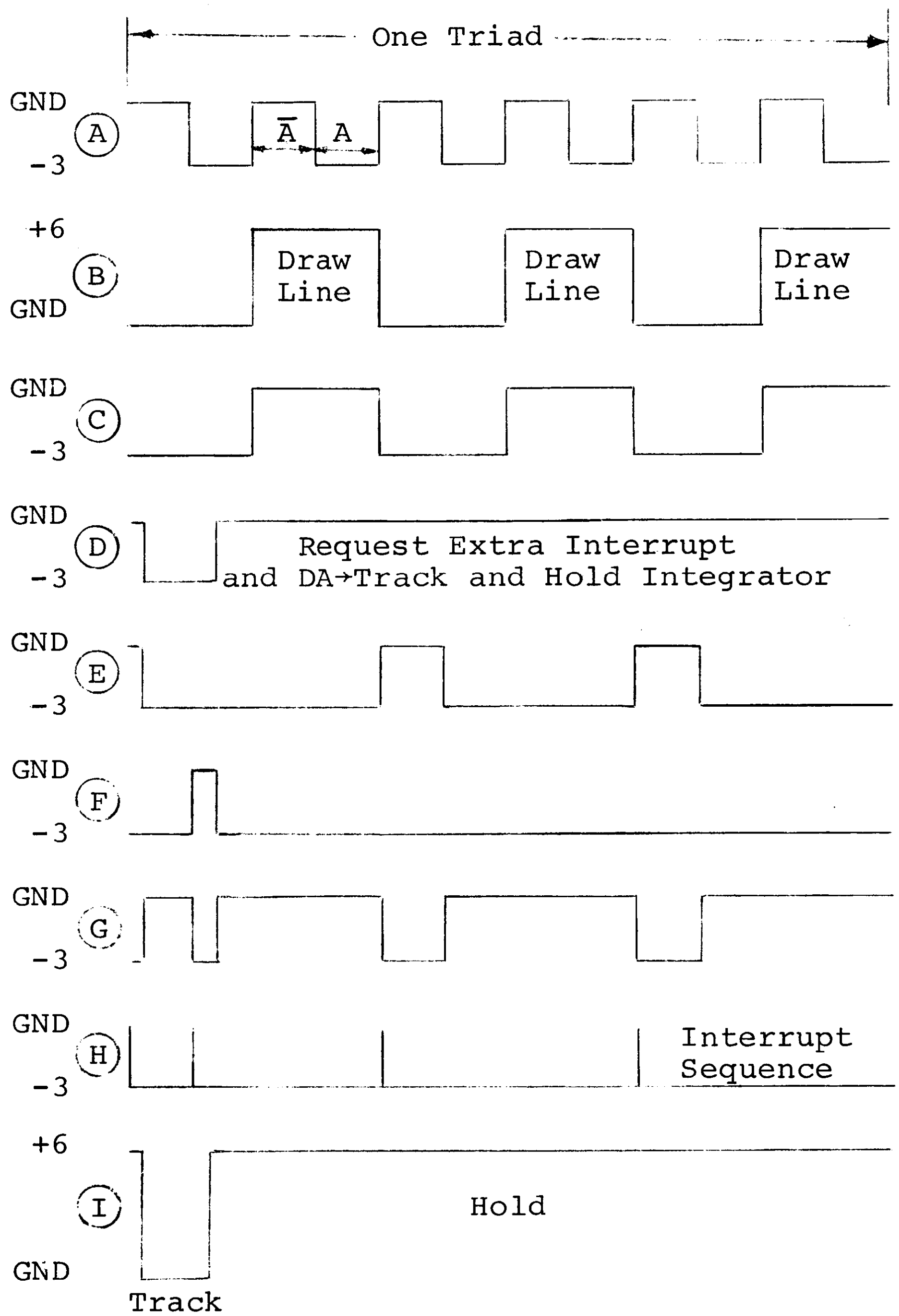


FIGURE A.9 SIGNALS AT SELECTED POINTS ON CONTROL BOARD on the non-vertex end point of a line. It is at ground to blank the line. Control line 7 is used to control the holding integrators for the coordinates of the triad vertex points. It is at ground to track and at -3 volts to hold the values. Control line 8 is used for routing the D-A values to the track and hold or line drawing integrators. It is at ground to apply the D-A voltage to the line drawing integrators and at -3 volts to apply the D-A voltage to the track and hold integrators. In addition, control line 8 permits an additional interrupt when it is at -3 volts.

Digital to analog converter channel 1 is used to transmit h and Δh. DA2 is used to transmit v and Δv. DA3 is used to transmit A(L,D). DA4 is unused.

Analog to digital converter channel 1 is used for the X velocity input. AD2 is used for the Y velocity input. AD3 is used for the Z velocity input. AD4 is used for the Θ angular velocity input. AD5 is used for the Φ angular velocity input. AD 6 is used for the Ψ angular velocity input. AD7 is used for the lateral head position input.

The triple precision (36 bit) x, y, and z coordinates of each point of the cube are stored in the variable inertial list (VIL) starting at 3000_8. There is a permanent (fixed) inertial list starting at 3200_8 (the list order is the same as the VIL) which is used to initialize the VIL. The coordinate values for one point at a time are taken from the VIL via autoindices 10, 11, and 12 and placed in temporary storage in page zero. The seventeen alternating order serial updating equations are implemented in triple precision. After the coordinates of the point have been updated, they are stored in their original place in the VIL via autoindices 13, 14, and 15. The perspective calculations are implemented in double precision. They include a digital saturation (located at 643_8 and 704_8) when either screen coordinate reaches the edge of the screen. The perspective transformed points are loaded into a display buffer via autoindex 16. There are two display buffers. While one is being loaded, the other is accessed via autoindex 17 for display on the oscilloscope screen. The transformed points are connected by lines grouped in triads according to the geometry specified in the reorganization section at 1600_8.

The flow diagram for the digital portion of the 3-D Display System is presented in Figures A.10.a to A.10.d for the main program and in Figures A.11.a to A.11.c for the interrupt servicing programs. The octal numbers next to blocks indicate the corresponding location in PDP-8 core memory. The system of numbering the points, lines and sides of the cube is shown in Figure A.12. An explanation of the symbolic names for variables, constants, and pointers used in the 3-D Display System appears on pages 86 to 92. The table of the octal core locations corresponding to symbolic names appears on pages 93 to 94. Finally, the pass three listing of the 3-D Display System in PAL-III assembly language appears on pages 95 to 121.

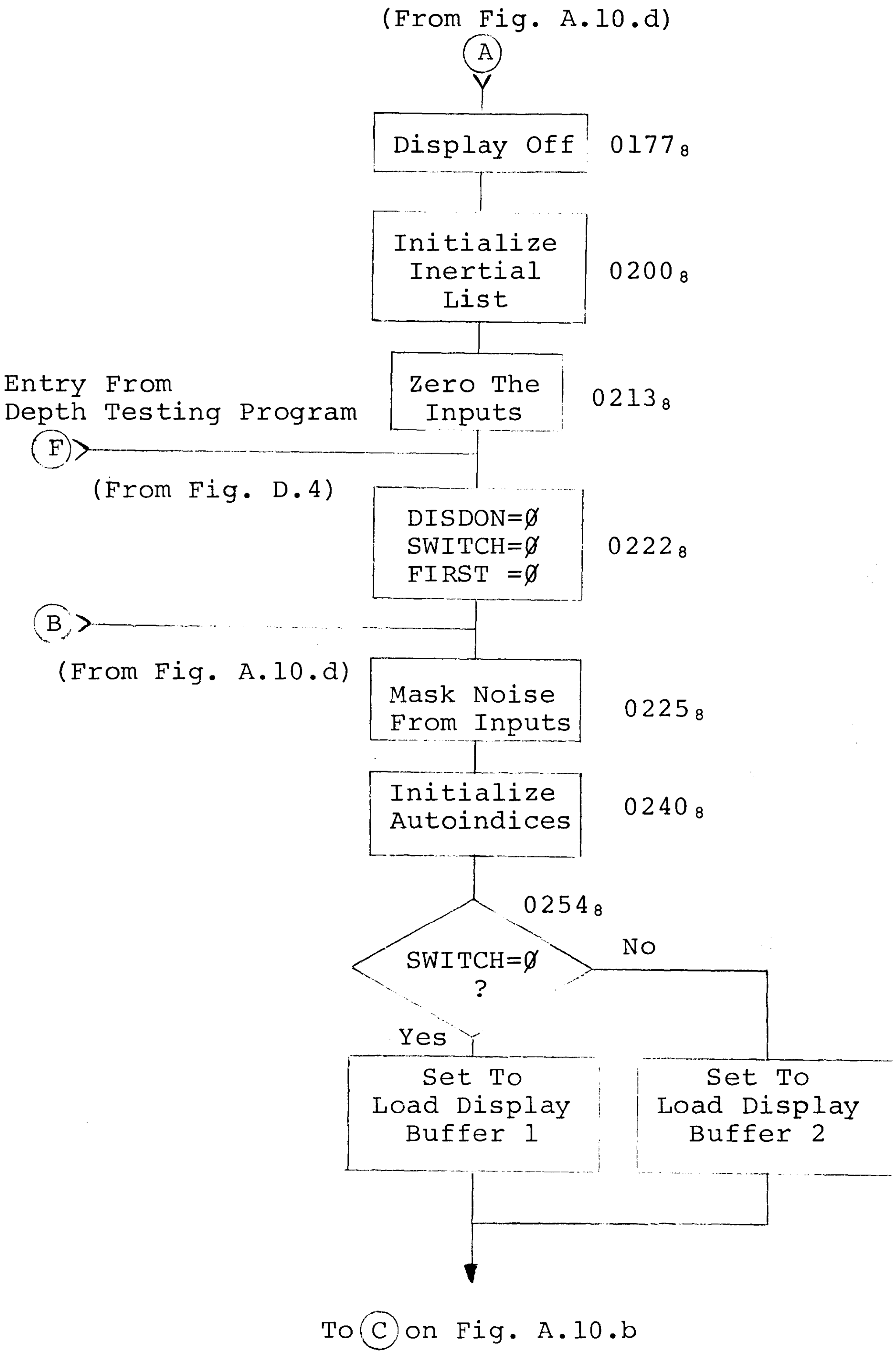
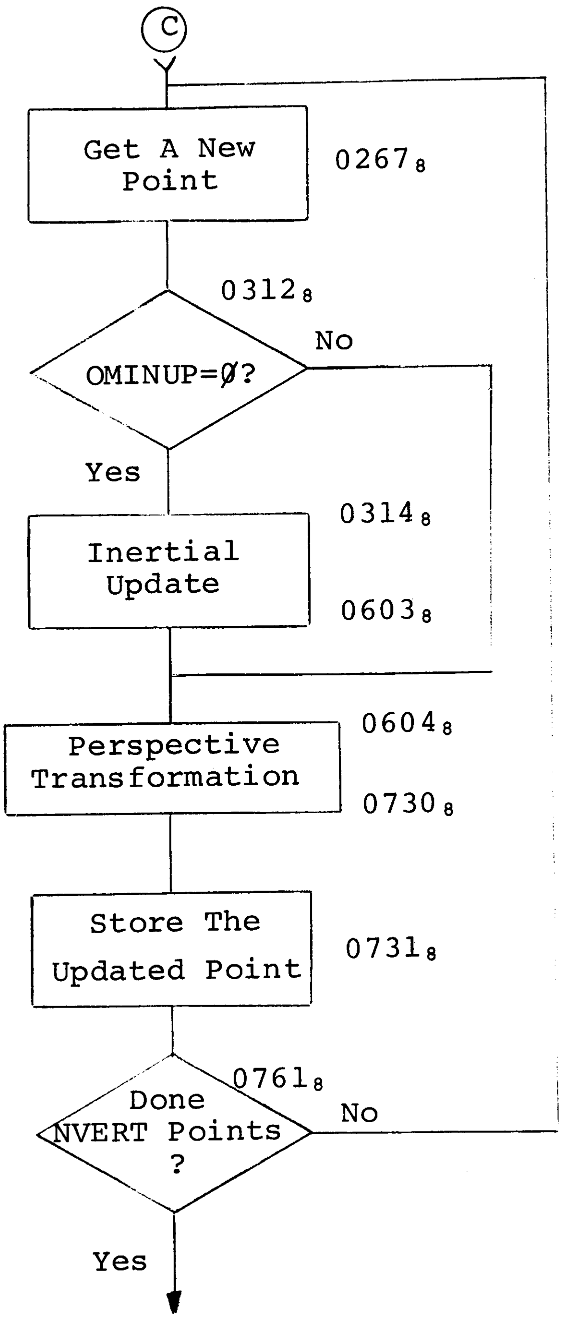


FIGURE A.10.a MAIN PROGRAM FLOW DIAGRAM

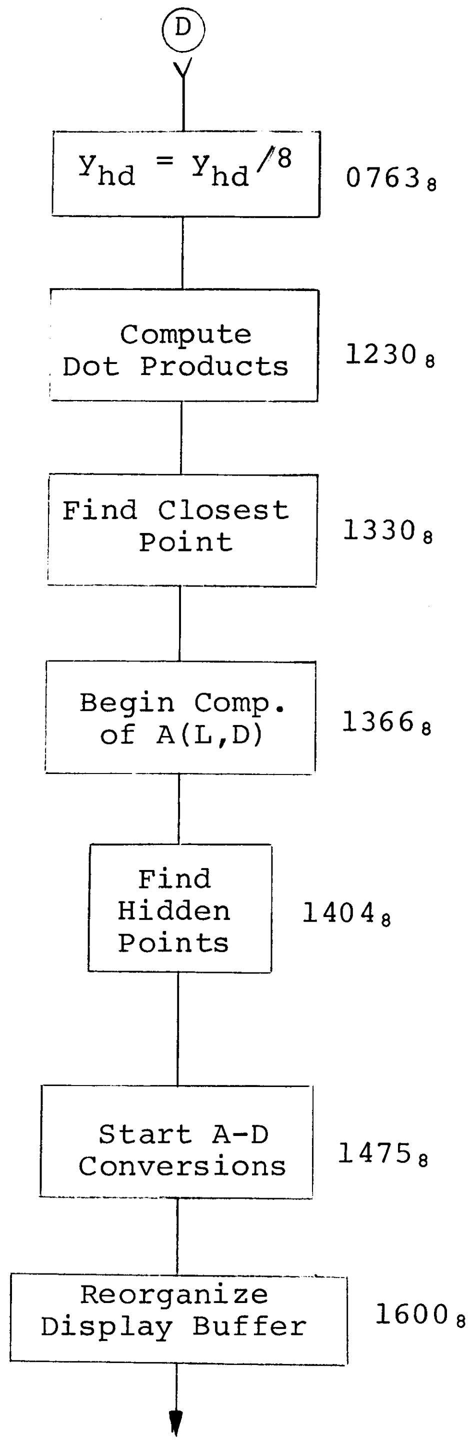
(From Fig. A.10.a)



To D on Fig. A.10.c

FIGURE A.10.b MAIN PROGRAM FLOW DIAGRAM

(From Fig. A.10.b)



To E on Fig. A.10.d

FIGURE A.10.c MAIN PROGRAM FLOW DIAGRAM

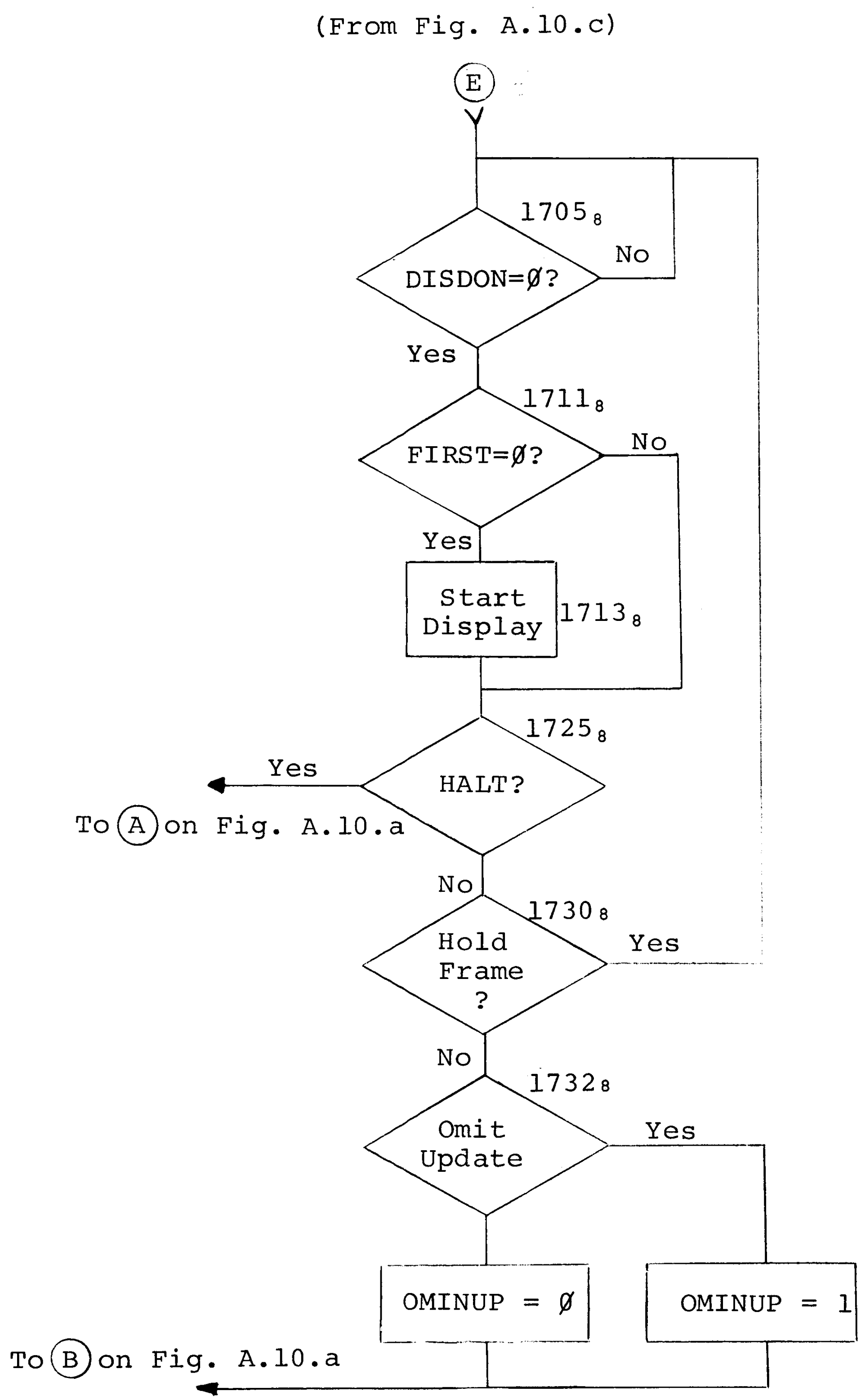


FIGURE A.10.d MAIN PROGRAM FLOW DIAGRAM

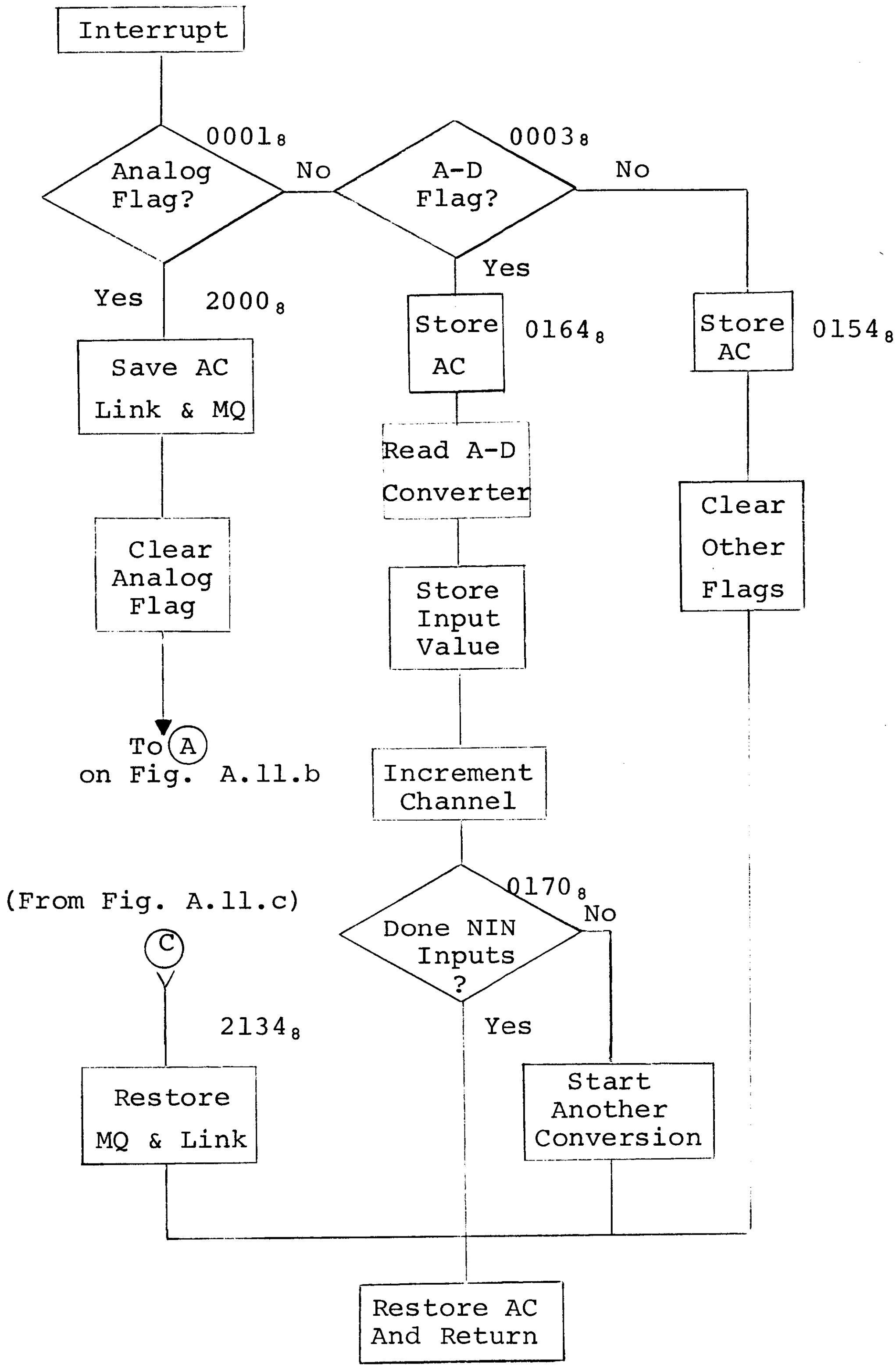


FIGURE A.11.a INTERRUPT FLOW DIAGRAM

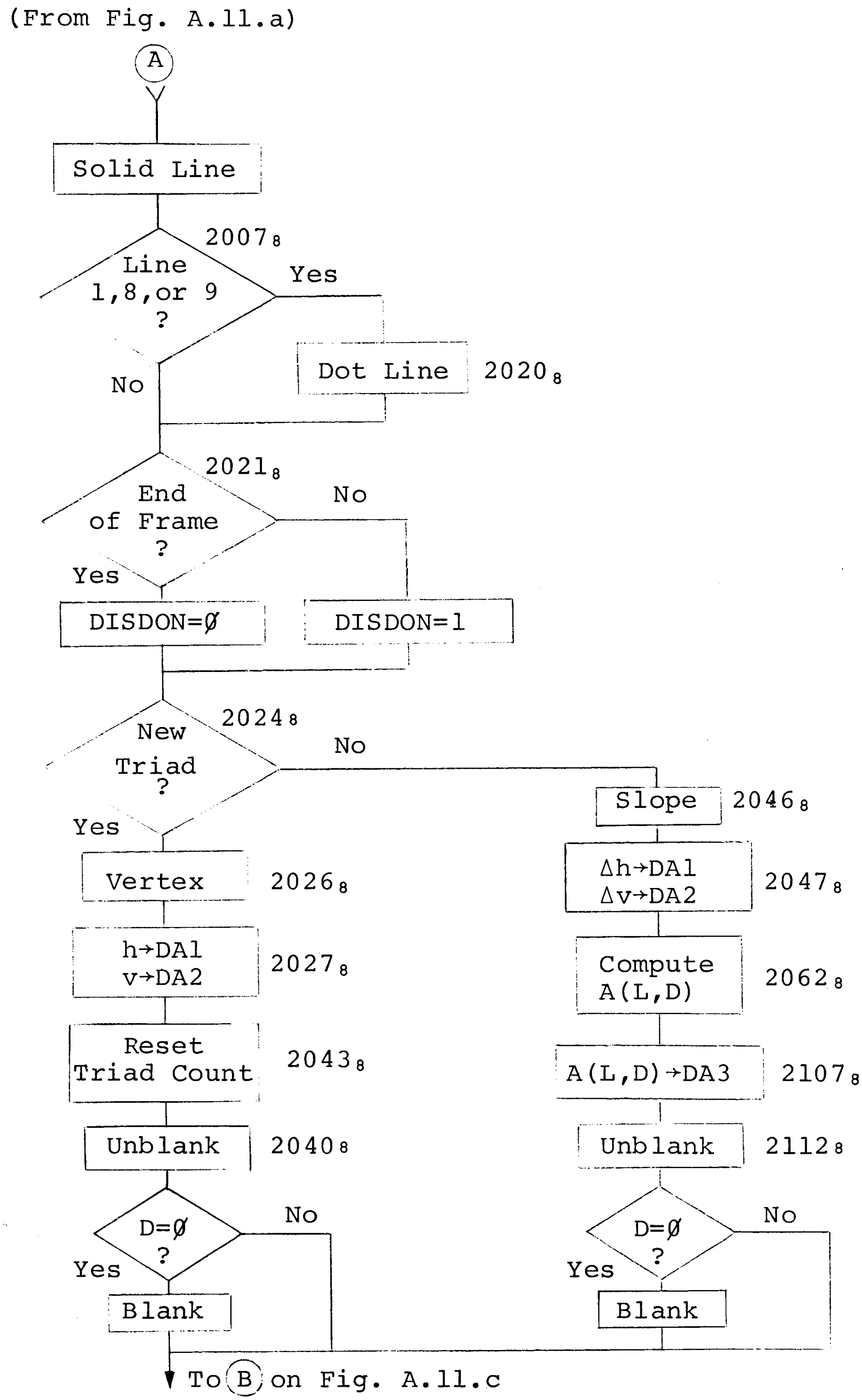


FIGURE A.11.b INTERRUPT FLOW DIAGRAM--
DISPLAY ROUTINE

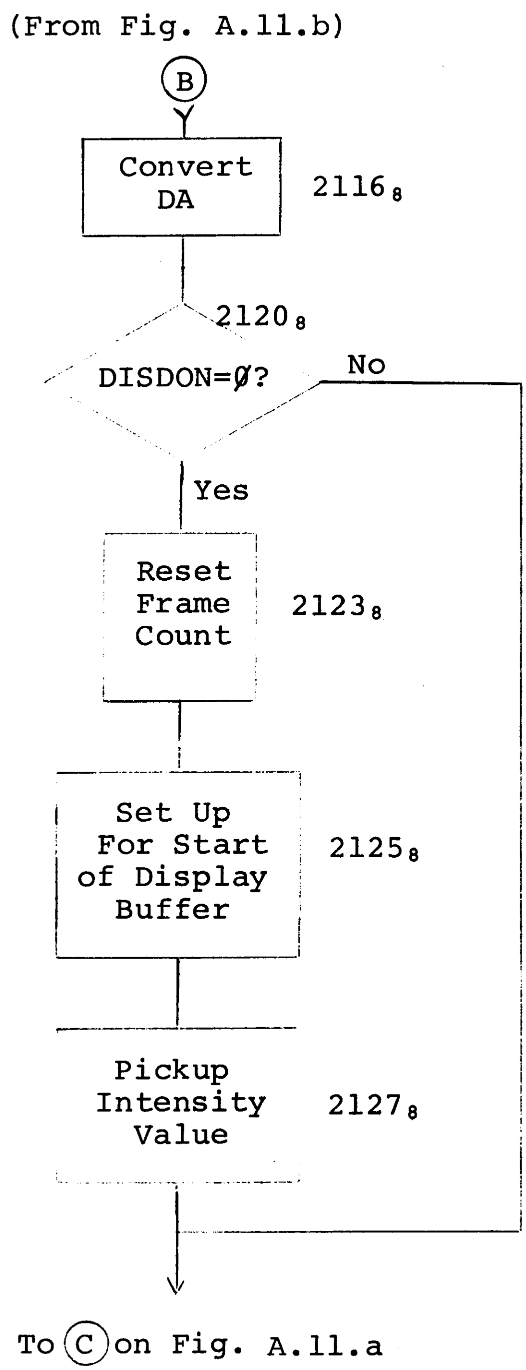


FIGURE A.11.c INTERRUPT FLOW DIAGRAM--
DISPLAY ROUTINE

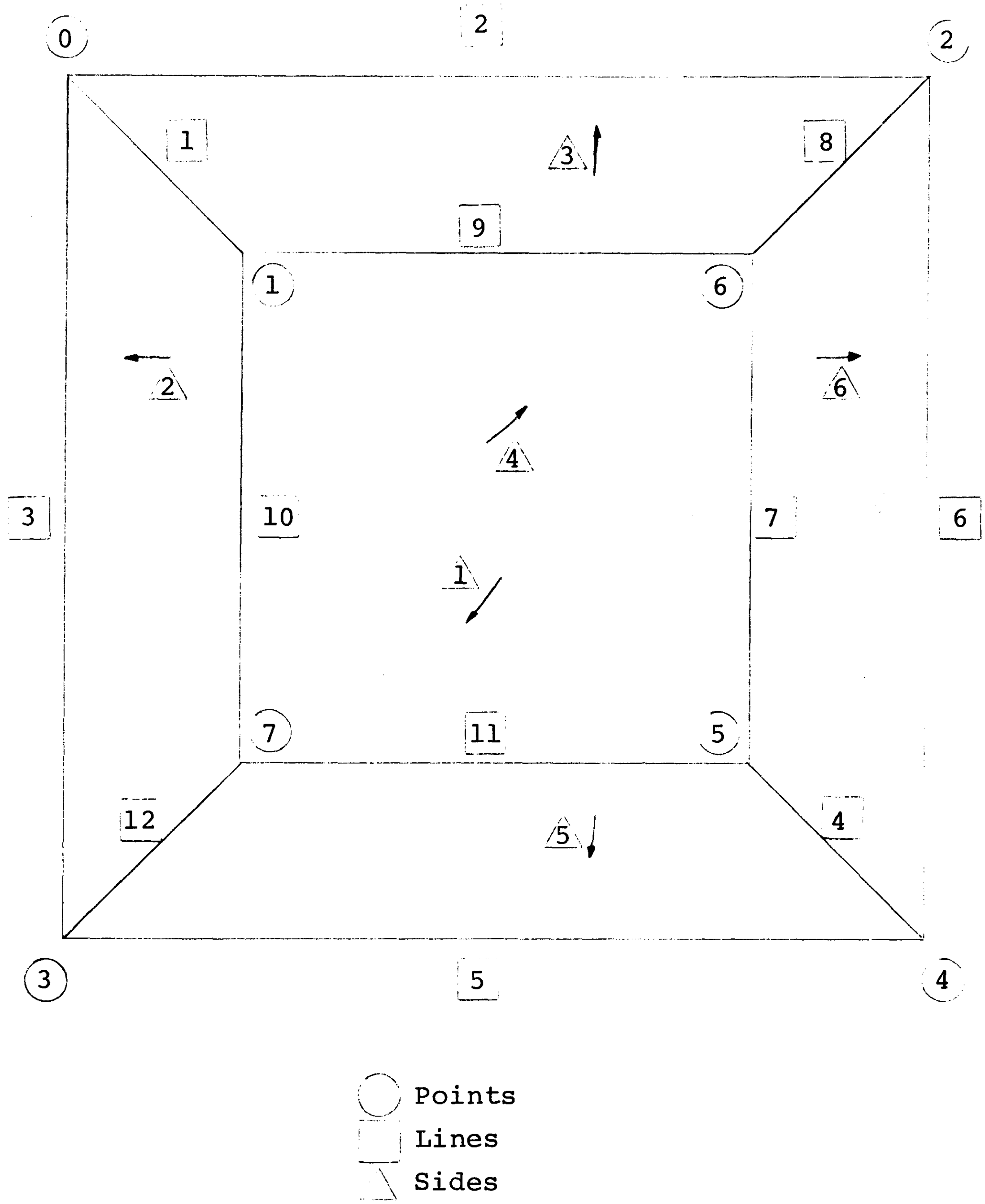


FIGURE A.12 NUMBERING OF THE PARTS OF THE CUBE

There are nine locations used for the triple precision coordinate of the current point of the cube being updated.

XH, XL and XLL are the triple precision X coordinate of the point currently being updated. XH is the most significant portion and XLL is the least significant portion. Similarly, YH, YL and YLL for the Y coordinate and ZH, ZL and ZLL for the Z coordinate.

There are seven inputs resulting from analog to digital conversions.

DELX, DELY and DELZ are the incremental translations per frame time of the coordinate system fixed to the vehicle.

THETA, PHI and PSI are the incremental rotations of the coordinate system.

DELYHD is the lateral head position.

There are three variables associated with the perspective transformations.

BOD is the eye to screen distance, B, divided by the eye to point distance, or "depth," XH.

H and V are the horizontal and vertical screen coordinates resulting from the perspective transform.

HIGH, LOW, LLOW and MPR are variables for intercommunicating with the single and double precision multiply subroutines.

There are five variables associated with sequencing control of the display subroutine.

PLIST is a pointer to the location before the display buffer which is to be currently displayed

FRAME is a counter to determine the end of a frame by counting interrupts.

FIRST is a variable which, when equal to Ø, indicates that this is the first frame and the display must be turned on; and when equal to 1, indicates that the display equipment is running.

DISDON is a variable used to synchronize the updating calculations to the display of a frame. DISDON is equal to 1 during the display of a frame so that the display buffer may not be changed and the updating calculations may not begin another cycle. At the end of a frame, DISDON is equal to Ø, the buffer is changed and the updating calculations allowed to proceed.

There are twelve variables used in the determination of hidden lines.

SIDE1, SIDE2, SIDE3, SIDE4, SIDE5 and SIDE6 are variables which are equal to 1 if the corresponding side of the cube is not visible and equal to Ø if it is visible.

PVX, PVY and PVZ are the X, Y and Z components of the vector from the observer's eye to a point of the cube.

NVX, NVY and NVZ are the X, Y and Z components of one of the three vectors normal to the sides that intersect at the point of the cube referred to above.

There are two variables used in finding the minimum depth for use in the computation of intensity as a function of depth.

PD is a pointer to the distance values in the display list. These distance values are equal to $XH^2 + YH^2 + ZH^2$.

DMIN is the minimum of these distances.

There are two other variables for sequencing and three commonly used variables.

CNTR and COUNT are counters used in several different places.

SAC is a location used to save the contents of the accumulator during the servicing of interrupts.

OMINUP is a variable which when equal to 1 prevents updating of the inertial list and when equal to Ø permits updating.

SWITCH is a variable which when equal to 1 says that display buffer 1 is to be used and when equal to Ø says that display buffer 2 is to be used.

C31 is used by intermediate calculation of A(L,D) to get pointer to scale location.

B is the eye to screen distance. C3 is used by the section that computes intensity as a function of depth.

SCALE1 is the constant used in the logarithmic calculations for intensity.

NFRAME is minus the number of interrupts in one frame.

MASK is a mask used to remove noise from the A-D inputs.

NIN is minus the number of inputs.

NILIST is the number of locations used in the inertial list which is equal to 3 locations times 3 coordinates times the number of points.

NVERT is the number of points in the object.

MASK1 is a mask used in the perspective routines to determine if the point is beyond the edge of the screen.

PLUS is +5 volts; that is, the righthand and top edges of the screen.

MINUS is -5 volts; that is, the lefthand and bottom edges of the screen.

CNØ3 is the constant -3 used by the two move subroutines in the buffer reorganization section of the program.

CN17 is the constant specifying the length of the table of pointers used in reorganizing the display list.

The following constants and variables are used by the display subroutines:

C5 and C11 are constants used to determine which lines are to be dotted.

NTRIAD is minus the number of interrupts per triad.

C61 is a constant to be added to the display list pointer to get the pointer to the intermediate value of A(L,D) that display buffer.

C1ØØØ is the constant C_1 in the intensity equation.

SCALE is used to store the portion of the intensity calculations resulting from depth.

PALOG is the pointer to the antilogarithm subroutine.

SLINK and MQ are used to store the contents of the link and multiplier-quotient register.

XICCOM and YICCOM are used to store the negative of the horizontal and vertical coordinates of the triad point.

P1 and P2 are used for intermediate storage in the calculation of the square of the line length.

There are several local variables used by subroutines.

SIGN is used by the double precision multiply subroutine to store the sign of the product.

PL is used by the same subroutine for intermediate storage.

SIGN1 is used by the single precision multiply subroutine.

SIGN2 is used by the fractional division subroutine to store the sign of the quotient.

The following pointers for indirect addressing are used:

LDELX points to the location before the A-D input storage.

LPRCL points to the start of the perspective calculations.

PBLANK points to the start of the calculations to blank hidden lines.

PBUFR1 points to the location before display buffer 1.

PBUFR2 points to the location before display buffer 2.

PDBUF1 points to the location before the table of pointers used in the reorganization of display buffer 1.

PDBUF2 points to the location before the table of pointers used in the reorganization of display buffer 2.

PDPTAB points to the location before the table of currently used pointers for reorganization of the display buffer.

PDPMUL points to the double precision multiply subroutine.

PDTPRD points to the subroutine to compute the dot product of two vectors.

PD1 points to the first depth entry in display buffer 1.

PD2 points to the first depth entry in display buffer 2.

PFRAD1 points to the fractional division subroutine.

PLOG points to the logarithm subroutine.

PMUL points to the single precision multiply subroutine.

PPRMIN points to the location before the permanent inertial list.

PREORG points to the start of the display buffer reorganization section of the program.

PREPEA points to the start of the loop to do the inertial update for another point of the cube.

PTHREE points to the start of a new updating cycle.

PTRANS points to the translation subroutine.

PUPDIS points to the display subroutine.

PXIN, PYIN and PZIN are pointers to the locations before the start of the X, Y and Z coordinate sections in the variable inertial list.

LPRCL	0073
MASK	0066
MASK1	0653
MINUS	0655
MLTPLR	2305
MLTPL1	2214
MLTPL2	2224
MPR	0055
MQ	2166
MUL	2271
M2	1736
NEG1	0656
NEG2	0714
NFRAME	0065
NILIST	0070
NIN	0067
NTRIAD	2164
NVERT	0071
NVX	0026
NVY	0027
NVZ	0030
OMINUP	0056
OTHER	0154
OUT	0151
PALOG	2176
PBFRTB	1752
PBLANK	0074
PBUFR1	0075
PBUFR2	0076
PD	0020
PDBUF1	0077
PDBUF2	0100
PDEPTH	0101
PDPMUL	0102
PDPTAB	1505
PDTPRD	0103
PD1	0104
PD2	0105
PERCAL	0604
PFRADI	0106
PHI	0035
PL	2270
PLIST	0044
PLOG	0107
PLUS	0654
PMUL	0110
PPRMIN	0111
PREORG	0112
PREPEA	0113
PRMIN	3200
PSI	0036
PTHREE	0114
PTRANS	0115

B	0061
BACK	2213
BFRTAB	1753
BLANK	1230
BOD	0040
BUFER1	3110
BUFER2	3310
CNTR	0041
CN03	1750
CN17	1751
COMP	2257
COMPLM	0123
COORD	0030
COUNT	0042
CVRTDA	2116
C1000	2174
C11	2163
C3	0062
C31	0063
C4000	0122
C5	2162
C61	2173
DBUF1	1506
DBUF2	1525
DELX	0031
DELY	0032
DELYHD	0037
DELZ	0033
DEPTH	2600
DISDON	0043
DIVSOR	2466
DMASK	0141
DMIN	0021
DPMUL	2200
DPTAB	1544
DTPROD	2652
FIRST	0047
FRADIV	2451
FRAME	0045
GO1	0671
GO2	0731
H	0050
HALT	0175
HIGH	0052
HOLD	1703
INLIST	0110
INPUTS	0007
INTAB	1200
LAST	2324
LDELX	0072
LLOW	0054
LOW	0053

PUPDIS	0116
PVX	0023
PVY	0024
PVZ	0025
PW1	2076
PW1A	2147
PXIN	0117
PYIN	0120
PZIN	0121
P1	2171
P2	2172
REORG	1600
REPEAT	0267
SAC	0057
SCALE	2175
SCALE1	0064
SETIC	2026
SIDE1	0022
SIDE2	0054
SIDE3	0050
SIDE4	0051
SIDE5	0040
SIDE6	0041
SIGN	2267
SIGN1	2326
SIGN2	2477
SLINK	2165
SLOPE	2046
SL1	0665
SL2	0723
SMALL	2144
SQ	2152
SQ1	2642
SRAD	0164
STAD	1475
START	0200
START2	0222
SWITCH	0060
THETA	0034
THREED	0225
TRANS	2400
TRIAD	0046
UPDIS	2000
V	0051
VERT	0010
XH	0020
XICCOM	2167
XIN	3000
XL	0021
XLL	0022
YH	0023
YICCOM	2170
YL	0024
YLL	0025
ZH	0026
ZL	0027
ZLL	0030

```
                XIN=3000
                PRMIN=3200
                INPUTS=7
                VERT=10

                COORD=VERT+VERT+VERT
                INLIST=COORD+COORD+COORD
                BUFER1=XIN+INLIST
                BUFER2=PRMIN+INLIST

                / INTERRUPT SERVICING ROUTINE

                *1
0001    6461    SKIF
0002    5516    JMP I Z PUPDIS
0003    6451    ADNF
0004    5164    JMP Z SRAD
0005    5154    JMP Z OTHER

                / VARIABLES

                *20
0020    0000    XH,0
0021    0000    XL,0
0022    0000    XLL,0
0023    0000    YH,0
0024    0000    YL,0
0025    0000    YLL,0
0026    0000    ZH,0
0027    0000    ZL,0
0030    0000    ZLL,0
0031    0000    DELX,0
0032    0000    DELY,0
0033    0000    DELZ,0
0034    0000    THETA,0
0035    0000    PHI,0
0036    0000    PSI,0
0037    0000    DELYHD,0
0040    0000    BOD,0
0041    0000    CNTR,0
0042    0000    COUNT,0
0043    0000    DISDON,0
0044    0000    PLIST,0
0045    0000    FRAME,0
0046    0000    TRIAD,0
0047    0000    FIRST,0
0050    0000    H,0
0051    0000    V,0
0052    0000    HIGH,0
0053    0000    LOW,0
0054    0000    LLOW,0
0055    0000    MPR,0
0056    0000    OMINUP,0
0057    0000    SAC,0
0060    0000    SWITCH,0

                / CONSTANTS

0061    0300    B,300
0062    0003    C3,3
0063    0031    C31,31
0064    6655    SCALE1,6655
0065    7760    NFRAME,-20
0066    7770    MASK,7770
0067    7771    NIN,-INPUTS
0070    0110    NILIST,INLIST
0071    0010    NVERT,VERT

/ VARIABLES FOR BLANKING

SIDE1=XLL
SIDE2=LLOW
SIDE3=H
SIDE4=V
SIDE5=BOD
SIDE6=CNTR
PVX=YH
PVY=YL
PVZ=YLL
NVX=ZH
NVY=ZL
NVZ=ZLL
```

```
/ POINTERS FOR INDIRECT ADDRESSING

0072  0030  LDELX,DELX-1
0073  0604  LPRCL,PERCAL
0074  1230  PBLANK,BLANK
0075  3107  PBUFR1,BUFER1-1
0076  3307  PBUFR2,BUFER2-1
0077  1505  PDBUF1,DBUF1-1
0100  1524  PDBUF2,DBUF2-1
0101  2600  PDEPTH,DEPTH
0102  2200  PDPMUL,DPMUL
0103  2652  PDTPRD,DTPROD
0104  3112  PD1,BUFER1+2
0105  3312  PD2,BUFER2+2
0106  2451  PFRADI,FRADIV
0107  6501  PLOG,6501
0110  2271  PMUL,MUL
0111  3177  PPRMIN,PRMIN-1
0112  1600  PREORG,REORG
0113  0267  PREPEA,REPEAT
0114  0225  PTHREE,THREED
0115  2400  PTRANS,TRANS
0116  2000  PUPDIS,UPDIS
0117  2777  PXIN,XIN-1
0120  3027  PYIN,XIN+COORD-1
0121  3057  PZIN,XIN+COORD+COORD-1

            PD=XH
            DMIN=XL

0122  4000  C4000,4000
0123  0000  COMPLM,0
0124  7041  CIA
0125  1122  TAD C4000
0126  7450  SNA
0127  7240  CLA CMA
0130  1122  TAD C4000
0131  5523  JMP I COMPLM
```

```
/ ROUTINE TO HANDLE
/ UNWANTED INTERRUPTS

0154  3057  OTHER,DCA Z SAC
0155  6036  KRB
0156  6042  TCF
0157  6772  MMCF
0160  7200  CLA
0161  1057  TAD Z SAC
0162  6001  ION
0163  5400  JMP I Z 0
```

```
            / SUBROUTINE TO MASK

            *141
0141  0000  DMASK,0
0142  7510  SPA
0143  5146  JMP .+3
0144  0066  AND Z MASK
0145  5151  JMP OUT
0146  7041  CIA
0147  0066  AND Z MASK
0150  7041  CIA
0151  7415  OUT,ASR
0152  0002  0002
0153  5541  JMP I Z DMASK
```

```
/ SERVICE ANALOG
/TO DIGITAL CONVERTER

0164  3057  SRAD,DCA Z SAC
0165  6534  ADRB
0166  3413  DCA I Z 13
0167  6544  ADIC
0170  2041  ISZ Z CNTR
0171  6532  ADCV
0172  1057  TAD Z SAC
0173  6001  ION
0174  5400  JMP I Z 0
```

```
                / HALT THE 3-D DISPLAY

0175   6452     HALT,CMR
0176   6404     AMPS
0177   7602     HLT CLA

                / INITIALIZE INERTIAL LIST

                *200
0200   1070     START,TAD Z NILIST
0201   7041     CIA
0202   3042     DCA Z COUNT
0203   1111     TAD Z PPRMIN
0204   3010     DCA Z 10
0205   1117     TAD Z PXIN
0206   3011     DCA Z 11
0207   1410     TAD I Z 10
0210   3411     DCA I Z 11
0211   2042     ISZ Z COUNT
0212   5207     JMP .-3

                / ZERO THE INPUTS

0213   1072     TAD Z LDELX
0214   3010     DCA Z 10
0215   1067     TAD Z NIN
0216   3042     DCA Z COUNT
0217   3410     DCA I Z 10
0220   2042     ISZ Z COUNT
0221   5217     JMP .-2

                / CONTINUE OR ALTERNATE START

0222   3043     START2,DCA Z DISDON
0223   3060     DCA Z SWITCH
0224   3047     DCA Z FIRST

                /  MASK THE NOISE FROM THE INPUTS

0225   1072     THREED,TAD Z LDELX
0226   3050     DCA Z H
0227   1067     TAD Z NIN
0230   7001     IAC
0231   3042     DCA Z COUNT
0232   2050     ISZ Z H
0233   1450     TAD I Z H
0234   4141     JMS Z DMASK
0235   3450     DCA I Z H
0236   2042     ISZ Z COUNT
0237   5232     JMP .-5
```

```
                / INITIALIZE AUTOINDICES

0240    1117    TAD Z PXIN
0241    3010    DCA Z 10
0242    1117    TAD Z PXIN
0243    3013    DCA Z 13
0244    1120    TAD Z PYIN
0245    3011    DCA Z 11
0246    1120    TAD Z PYIN
0247    3014    DCA Z 14
0250    1121    TAD Z PZIN
0251    3012    DCA Z 12
0252    1121    TAD Z PZIN
0253    3015    DCA Z 15

                / SET THE BUFFER TO BE USED

0254    1060    TAD Z SWITCH
0255    7640    SZA CLA
0256    5262    JMP .+4
0257    1076    TAD Z PBUFR2
0260    3016    DCA Z 16
0261    5264    JMP .+3
0262    1075    TAD Z PBUFR1
0263    3016    DCA Z 16
0264    1071    TAD Z NVERT
0265    7041    CIA
0266    3042    DCA Z COUNT

                / GET A NEW POINT

0267    1410    REPEAT, TAD I Z 10
0270    3020    DCA Z XH
0271    1410    TAD I Z 10
0272    3021    DCA Z XL
0273    1410    TAD I Z 10
0274    3022    DCA Z XLL
0275    1411    TAD I Z 11
0276    3023    DCA Z YH
0277    1411    TAD I Z 11
0300    3024    DCA Z YL
0301    1411    TAD I Z 11
0302    3025    DCA Z YLL
0303    1412    TAD I Z 12
0304    3026    DCA Z ZH
0305    1412    TAD I Z 12
0306    3027    DCA Z ZL
0307    1412    TAD I Z 12
0310    3030    DCA Z ZLL
0311    1056    TAD Z OMINUP
0312    7640    SZA CLA
0313    5473    JMP I Z LPRCL

0314    4515    JMS I Z PTRANS
```

/ ROLL ALGORITHM PART 1

```
0315   1027   TAD Z ZL
0316   3053   DCA Z LOW
0317   1026   TAD Z ZH
0320   3052   DCA Z HIGH
0321   1035   TAD Z PHI
0322   4502   JMS I Z PDPMUL
0323   1025   TAD Z YLL
0324   3025   DCA Z YLL
0325   7004   RAL
0326   1053   TAD Z LOW
0327   1024   TAD Z YL
0330   3024   DCA Z YL
0331   7004   RAL
0332   1052   TAD Z HIGH
0333   1023   TAD Z YH
0334   3023   DCA Z YH
0335   1024   TAD Z YL
0336   3053   DCA Z LOW
0337   1023   TAD Z YH
0340   3052   DCA Z HIGH
0341   1035   TAD Z PHI
0342   7041   CIA
0343   4502   JMS I Z PDPMUL
0344   1030   TAD Z ZLL
0345   3030   DCA Z ZLL
0346   7004   RAL
0347   1053   TAD Z LOW
0350   1027   TAD Z ZL
0351   3027   DCA Z ZL
0352   7004   RAL
0353   1052   TAD Z HIGH
0354   1026   TAD Z ZH
0355   3026   DCA Z ZH
```

/ PITCH ALGORITHM PART 1

```
0356   1021   TAD Z XL
0357   3053   DCA Z LOW
0360   1020   TAD Z XH
0361   3052   DCA Z HIGH
0362   1034   TAD Z THETA
0363   4502   JMS I Z PDPMUL
0364   1030   TAD Z ZLL
0365   3030   DCA Z ZLL
0366   7004   RAL
0367   1053   TAD Z LOW
0370   1027   TAD Z ZL
0371   3027   DCA Z ZL
0372   7004   RAL
0373   1052   TAD Z HIGH
0374   1026   TAD Z ZH
0375   3026   DCA Z ZH
0376   1027   TAD Z ZL
0377   3053   DCA Z LOW
0400   1026   TAD Z ZH
0401   3052   DCA Z HIGH
0402   1034   TAD Z THETA
0403   7041   CIA
0404   4502   JMS I Z PDPMUL
0405   1022   TAD Z XLL
0406   3022   DCA Z XLL
0407   7004   RAL
0410   1053   TAD Z LOW
0411   1021   TAD Z XL
0412   3021   DCA Z XL
0413   7004   RAL
0414   1052   TAD Z HIGH
0415   1020   TAD Z XH
0416   3020   DCA Z XH
```

```
            / YAW ALGORITHM

0417  1024  TAD Z YL
0420  3053  DCA Z LOW
0421  1023  TAD Z YH
0422  3052  DCA Z HIGH
0423  1036  TAD Z PSI
0424  4502  JMS I PDPMUL
0425  1022  TAD Z XLL
0426  3022  DCA Z XLL
0427  7004  RAL
0430  1053  TAD Z LOW
0431  1021  TAD Z XL
0432  3021  DCA Z XL
0433  7004  RAL
0434  1052  TAD Z HIGH
0435  1020  TAD Z XH
0436  3020  DCA Z XH
0437  1021  TAD Z XL
0440  3053  DCA Z LOW
0441  1020  TAD Z XH
0442  3052  DCA Z HIGH
0443  1036  TAD Z PSI
0444  7164  CLL CMA CML RAL
0445  7001  IAC
0446  4502  JMS I Z PDPMUL
0447  1025  TAD Z YLL
0450  3025  DCA Z YLL
0451  7004  RAL
0452  1053  TAD Z LOW
0453  1024  TAD Z YL
0454  3024  DCA Z YL
0455  7004  RAL
0456  1052  TAD Z HIGH
0457  1023  TAD Z YH
0460  3023  DCA Z YH
0461  1024  TAD Z YL
0462  3053  DCA Z LOW
0463  1023  TAD Z YH
0464  3052  DCA Z HIGH
0465  1036  TAD Z PSI
0466  4502  JMS I Z PDPMUL
0467  1022  TAD Z XLL
0470  3022  DCA Z XLL
0471  7004  RAL
0472  1053  TAD Z LOW
0473  1021  TAD Z XL
0474  3021  DCA Z XL
0475  7004  RAL
0476  1052  TAD Z HIGH
0477  1020  TAD Z XH
0500  3020  DCA Z XH
```

/ PITCH ALGORITHM PART 2

```
0501   1027   TAD Z ZL
0502   3053   DCA Z LOW
0503   1026   TAD Z ZH
0504   3052   DCA Z HIGH
0505   1034   TAD Z THETA
0506   7041   CIA
0507   4502   JMS I PDPMUL
0510   1022   TAD Z XLL
0511   3022   DCA Z XLL
0512   7004   RAL
0513   1053   TAD Z LOW
0514   1021   TAD Z XL
0515   3021   DCA Z XL
0516   7004   RAL
0517   1052   TAD Z HIGH
0520   1020   TAD Z XH
0521   3020   DCA Z XH
0522   1021   TAD Z XL
0523   3053   DCA Z LOW
0524   1020   TAD Z XH
0525   3052   DCA Z HIGH
0526   1034   TAD Z THETA
0527   4502   JMS I Z PDPMUL
0530   1030   TAD Z ZLL
0531   3030   DCA Z ZLL
0532   7004   RAL
0533   1053   TAD Z LOW
0534   1027   TAD Z ZL
0535   3027   DCA Z ZL
0536   7004   RAL
0537   1052   TAD Z HIGH
0540   1026   TAD Z ZH
0541   3026   DCA Z ZH
```

/ROLL ALGORITHM PART 2

```
0542   1024   TAD Z YL
0543   3053   DCA Z LOW
0544   1023   TAD Z YH
0545   3052   DCA Z HIGH
0546   1035   TAD Z PHI
0547   7041   CIA
0550   4502   JMS I PDPMUL
0551   1030   TAD Z ZLL
0552   3030   DCA Z ZLL
0553   7004   RAL
0554   1053   TAD Z LOW
0555   1027   TAD Z ZL
0556   3027   DCA Z ZL
0557   7004   RAL
0560   1052   TAD Z HIGH
0561   1026   TAD Z ZH
0562   3026   DCA Z ZH
0563   1027   TAD Z ZL
0564   3053   DCA Z LOW
0565   1026   TAD Z ZH
0566   3052   DCA Z HIGH
0567   1035   TAD Z PHI
0570   4502   JMS I PDPMUL
0571   1025   TAD Z YLL
0572   3025   DCA Z YLL
0573   7004   RAL
0574   1053   TAD Z LOW
0575   1024   TAD Z YL
0576   3024   DCA Z YL
0577   7004   RAL
0600   1052   TAD Z HIGH
0601   1023   TAD Z YH
0602   3023   DCA Z YH

0603   4515   JMS I Z PTRANS
```

/ PERSPECTIVE TRANSFORMATIONS

```
0604    4506    PERCAL,JMS I Z PFRADI
0605    7621    CLA MQL
0606    1037    TAD Z DELYHD
0607    4123    JMS Z COMPLM
0610    7415    ASR
0611    0004    0004
0612    1023    TAD Z YH
0613    3052    DCA Z HIGH
0614    7100    CLL
0615    7701    CLA MQA
0616    1024    TAD Z YL
0617    3053    DCA Z LOW
0620    7430    SZL
0621    2052    ISZ Z HIGH
0622    7000    NOP
0623    1040    TAD Z BOD
0624    4502    JMS I Z PDPMUL
0625    7621    CLA MQL
0626    1037    TAD Z DELYHD
0627    7415    ASR
0630    0005    0005
0631    1052    TAD Z HIGH
0632    3052    DCA Z HIGH
0633    7100    CLL
0634    7701    CLA MQA
0635    1053    TAD Z LOW
0636    7421    MQL
0637    7430    SZL
0640    2052    ISZ Z HIGH
0641    7000    NOP
0642    1052    TAD Z HIGH
0643    7510    SPA
0644    5256    JMP NEG1
0645    0253    AND MASK1
0646    7650    SNA CLA
0647    5265    JMP SL1
0650    1254    TAD PLUS
0651    3050    DCA Z H
0652    5271    JMP GO1
0653    7760    MASK1,7760
0654    1777    PLUS,1777
0655    6000    MINUS,6000
0656    7040    NEG1,CMA
0657    0253    AND MASK1
0660    7650    SNA CLA
0661    5265    JMP SL1
0662    1255    TAD MINUS
0663    3050    DCA Z H
0664    5271    JMP GO1
0665    1052    SL1,TAD Z HIGH
0666    7413    SHL
0667    0005    0005
0670    3050    DCA Z H

0671    1026    GO1,TAD Z ZH
0672    3052    DCA Z HIGH
0673    1027    TAD Z ZL
0674    3053    DCA Z LOW
0675    1040    TAD Z BOD
0676    7041    CIA
0677    4502    JMS I Z PDPMUL
0700    7200    CLA
0701    1053    TAD Z LOW
0702    7421    MQL
0703    1052    TAD HIGH
0704    7510    SPA
0705    5314    JMP NEG2
0706    0253    AND MASK1
0707    7650    SNA CLA
0710    5323    JMP SL2
0711    1254    TAD PLUS
0712    3051    DCA Z V
0713    5331    JMP GO2
0714    7040    NEG2,CMA
0715    0253    AND MASK1
0716    7650    SNA CLA
0717    5323    JMP SL2
0720    1255    TAD MINUS
0721    3051    DCA Z V
0722    5331    JMP GO2
0723    1053    SL2,TAD Z LOW
0724    7421    MQL
0725    1052    TAD Z HIGH
0726    7413    SHL
0727    0005    0005
0730    3051    DCA Z V
```

```
                / STORE THE UPDATED POINT

0731    1020    GO2,TAD Z XH
0732    3413    DCA I Z 13
0733    1021    TAD Z XL
0734    3413    DCA I Z 13
0735    1022    TAD Z XLL
0736    3413    DCA I Z 13
0737    1023    TAD Z YH
0740    3414    DCA I Z 14
0741    1024    TAD Z YL
0742    3414    DCA I Z 14
0743    1025    TAD Z YLL
0744    3414    DCA I Z 14
0745    1026    TAD Z ZH
0746    3415    DCA I Z 15
0747    1027    TAD Z ZL
0750    3415    DCA I Z 15
0751    1030    TAD Z ZLL
0752    3415    DCA I Z 15
0753    1050    TAD Z H
0754    3416    DCA I Z 16
0755    1051    TAD Z V
0756    3416    DCA I Z 16
0757    4501    JMS I PDEPTH
0760    3416    DCA I Z 16

0761    2042    ISZ COUNT
0762    5513    JMP I PREPEA
0763    1037    TAD DELYHD
0764    7510    SPA
0765    5371    JMP .+4
0766    7415    ASR
0767    0004    0004
0770    5375    JMP .+5
0771    4123    JMS COMPLM
0772    7415    ASR
0773    0004    0004
0774    7041    CIA
0775    3037    DCA DELYHD
0776    5474    JMP I Z PBLANK
```

```
                / ROUTINE TO BLANK HIDDEN SIDES
                / OF CUBE BASED ON DOT PRODUCT
                / OF THE INWARD NORMAL VECTORS
                / AND THE LINE OF SIGHT TO EYE

                *1200
1200    3000    INTAB,XIN
1201    3003    XIN+3
1202    3006    XIN+6
1203    3011    XIN+11
1204    3014    XIN+14
1205    3017    XIN+17
1206    3022    XIN+22
1207    3025    XIN+25
1210    3030    XIN+30
1211    3033    XIN+33
1212    3036    XIN+36
1213    3041    XIN+41
1214    3044    XIN+44
1215    3047    XIN+47
1216    3052    XIN+52
1217    3055    XIN+55
1220    3060    XIN+60
1221    3063    XIN+63
1222    3066    XIN+66
1223    3071    XIN+71
1224    3074    XIN+74
1225    3077    XIN+77
1226    3102    XIN+102
1227    3105    XIN+105

1230    1600    BLANK,TAD I INTAB
1231    3023    DCA Z PVX
1232    1037    TAD Z DELYHD
1233    4123    JMS Z COMPLM
1234    1610    TAD I INTAB+10
1235    3024    DCA Z PVY
1236    1620    TAD I INTAB+20
1237    3025    DCA Z PVZ
1240    1601    TAD I INTAB+1
1241    3026    DCA Z NVX
1242    1611    TAD I INTAB+11
1243    3027    DCA Z NVY
1244    1621    TAD I INTAB+21
1245    3030    DCA Z NVZ
1246    4503    JMS I Z PDTPRD
1247    3022    DCA Z SIDE1
1250    1602    TAD I INTAB+2
1251    3026    DCA Z NVX
1252    1612    TAD I INTAB+12
1253    3027    DCA Z NVY
1254    1622    TAD I INTAB+22
1255    3030    DCA Z NVZ
1256    4503    JMS I Z PDTPRD
1257    3054    DCA Z SIDE2
1260    1603    TAD I INTAB+3
1261    3026    DCA Z NVX
1262    1613    TAD I INTAB+13
1263    3027    DCA Z NVY
1264    1623    TAD I INTAB+23
1265    3030    DCA Z NVZ
1266    4503    JMS I Z PDTPRD
1267    3050    DCA Z SIDE3
1270    1605    TAD I INTAB+5
1271    3023    DCA Z PVX
1272    1037    TAD Z DELYHD
1273    4123    JMS Z COMPLM
1274    1615    TAD I INTAB+15
1275    3024    DCA Z PVY
1276    1625    TAD I INTAB+25
1277    3025    DCA Z PVZ
1300    1604    TAD I INTAB+4
1301    3026    DCA Z NVX
1302    1614    TAD I INTAB+14
1303    3027    DCA Z NVY
1304    1624    TAD I INTAB+24
1305    3030    DCA Z NVZ
1306    4503    JMS I Z PDTPRD
1307    3051    DCA Z SIDE4
1310    1606    TAD I INTAB+6
1311    3026    DCA Z NVX
1312    1616    TAD I INTAB+16
1313    3027    DCA Z NVY
1314    1626    TAD I INTAB+26
1315    3030    DCA Z NVZ
1316    4503    JMS I Z PDTPRD
1317    3040    DCA Z SIDE5
1320    1607    TAD I INTAB+7
1321    3026    DCA Z NVX
1322    1617    TAD I INTAB+17
1323    3027    DCA Z NVY
1324    1627    TAD I INTAB+27
1325    3030    DCA Z NVZ
1326    4503    JMS I Z PDTPRD
1327    3041    DCA Z SIDE6
```

```
                / START FIRST PART OF A(L,D) COMPUTATION

1330  1060  TAD Z SWITCH
1331  7640  SZA CLA
1332  5336  JMP .+4
1333  1105  TAD PD2
1334  3020  DCA PD
1335  5340  JMP .+3
1336  1104  TAD PD1
1337  3020  DCA PD
1340  7240  CLA CMA
1341  1071  TAD Z NVERT
1342  7041  CIA
1343  3042  DCA Z COUNT
1344  1420  TAD I PD
1345  3021  DCA DMIN           /MIN D**2
1346  1020  TAD PD
1347  1062  TAD C3
1350  3020  DCA PD
1351  1420  TAD I PD
1352  7041  CIA
1353  1021  TAD DMIN
1354  7750  SPA SNA CLA
1355  5360  JMP .+3
1356  1420  TAD I PD
1357  3021  DCA DMIN
1360  2042  ISZ COUNT
1361  5346  JMP .-13
1362  1020  TAD PD
1363  1063  TAD C31
1364  3020  DCA PD
1365  7421  MQL
1366  1021  TAD DMIN
1367  6002  IOF
1370  4507  JMS I Z PLOG
1371  6001  ION
1372  7425  MQL MUY
1373  5253  5253
1374  3021  DCA DMIN
1375  7501  MQA
1376  7710  SPA CLA
1377  7001  IAC
1400  1021  TAD DMIN
1401  7041  CIA
1402  1064  TAD SCALE1
1403  3420  DCA I PD
```

```
          /HIDDEN SIDE BLANKING CONTINUED

1404   1060   TAD Z SWITCH
1405   7640   SZA CLA
1406   5212   JMP .+4
1407   1100   TAD Z PDBUF2
1410   3014   DCA Z 14
1411   5214   JMP .+3
1412   1077   TAD Z PDBUF1
1413   3014   DCA Z 14
1414   1305   TAD PDPTAB
1415   3015   DCA Z 15
1416   1071   TAD Z NVERT
1417   7041   CIA
1420   3042   DCA Z COUNT
1421   1414   TAD I Z 14
1422   3415   DCA I Z 15
1423   2042   ISZ Z COUNT
1424   5221   JMP .-3

              /  CALCULATIONS OF VISABLE VERTICES

1425   1022   TAD Z SIDE1
1426   0054   AND Z SIDE2
1427   0050   AND Z SIDE3
1430   7640   SZA CLA
1431   3744   DCA I DPTAB
1432   1054   TAD Z SIDE2
1433   0050   AND Z SIDE3
1434   0051   AND Z SIDE4
1435   7640   SZA CLA
1436   3745   DCA I DPTAB+1
1437   1022   TAD Z SIDE1
1440   0050   AND Z SIDE3
1441   0041   AND Z SIDE6
1442   7640   SZA CLA
1443   3746   DCA I DPTAB+2
1444   1022   TAD Z SIDE1
1445   0054   AND Z SIDE2
1446   0040   AND Z SIDE5
1447   7640   SZA CLA
1450   3747   DCA I DPTAB+3
1451   1022   TAD Z SIDE1
1452   0040   AND Z SIDE5
1453   0041   AND Z SIDE6
1454   7640   SZA CLA
1455   3750   DCA I DPTAB+4
1456   1051   TAD Z SIDE4
1457   0040   AND Z SIDE5
1460   0041   AND Z SIDE6
1461   7640   SZA CLA
1462   3751   DCA I DPTAB+5
```

```
1463  1050  TAD Z SIDE3
1464  0051  AND Z SIDE4
1465  0041  AND Z SIDE6
1466  7640  SZA CLA
1467  3752  DCA I DPTAB+6
1470  1054  TAD Z SIDE2
1471  0051  AND Z SIDE4
1472  0040  AND Z SIDE5
1473  7640  SZA CLA
1474  3753  DCA I DPTAB+7

            /     START A-D CONVERSIONS

1475  1067  STAD,TAD Z NIN     /NUMBER OF CONVERSIONS
1476  3041  DCA Z CNTR
1477  6545  ADCC ADIC          /SET TO CHANNEL 1
1500  1072  TAD Z LDELX        /LOCATION OF INPUT STORAGE-1
1501  3013  DCA Z 13
1502  6532  ADCV               /START CONVERSION
1503  6001  ION                /INTERRUPT ON
1504  5512  JMP I Z PREORG

1505  1543  PDPTAB,DPTAB-1
1506  3112  DBUF1,BUFER1+2     /BUFFER1
1507  3115  BUFER1+5
1510  3120  BUFER1+10
1511  3123  BUFER1+13
1512  3126  BUFER1+16
1513  3131  BUFER1+21
1514  3134  BUFER1+24
1515  3137  BUFER1+27
1516  3142  BUFER1+32
1517  3145  BUFER1+35
1520  3150  BUFER1+40
1521  3153  BUFER1+43
1522  3156  BUFER1+46
1523  3161  BUFER1+51
1524  3164  BUFER1+54
1525  3312  DBUF2,BUFER2+2     /BUFFER 2
1526  3315  BUFER2+5
1527  3320  BUFER2+10
1530  3323  BUFER2+13
1531  3326  BUFER2+16
1532  3331  BUFER2+21
1533  3334  BUFER2+24
1534  3337  BUFER2+27
1535  3342  BUFER2+32
1536  3345  BUFER2+35
1537  3350  BUFER2+40
1540  3353  BUFER2+43
1541  3356  BUFER2+46
1542  3361  BUFER2+51
1543  3364  BUFER2+54
```

```
1544  0000  DPTAB,0
1545  0000  0
1546  0000  0
1547  0000  0
1550  0000  0
1551  0000  0
1552  0000  0
1553  0000  0
```

```
                / OPERATE ON BUFFER TO ORGANIZE DISPLAY LIST

                *1600
1600    1060    REORG,TAD Z SWITCH
1601    7640    SZA CLA
1602    5211    JMP .+7
1603    1076    TAD Z PBUFR2
1604    3044    DCA Z PLIST
1605    1100    TAD Z PDBUF2
1606    3015    DCA Z 15
1607    7040    CMA
1610    5215    JMP .+5
1611    1075    TAD Z PBUFR1
1612    3044    DCA Z PLIST
1613    1077    TAD Z PDBUF1
1614    3015    DCA Z 15
1615    3060    DCA Z SWITCH
1616    1352    TAD PBFRTB
1617    3016    DCA Z 16
1620    1351    TAD CN17
1621    3042    DCA Z COUNT
1622    1415    TAD I Z 15
1623    3416    DCA I Z 16
1624    2042    ISZ Z COUNT
1625    5222    JMP .-3
1626    1357    TAD BFRTAB+4
1627    3016    DCA Z 16
1630    1357    TAD BFRTAB+4
1631    3012    DCA Z 12
1632    1363    TAD BFRTAB+10
1633    3015    DCA Z 15
1634    1370    TAD BFRTAB+15
1635    3014    DCA Z 14
1636    4336    JMS M2
1637    1360    TAD BFRTAB+5
1640    3016    DCA Z 16
1641    1361    TAD BFRTAB+6
1642    3012    DCA Z 12
1643    1362    TAD BFRTAB+7
1644    3015    DCA Z 15
1645    1366    TAD BFRTAB+13
1646    3014    DCA Z 14
1647    4336    JMS M2
1650    1353    TAD BFRTAB
1651    3016    DCA Z 16
1652    1353    TAD BFRTAB
1653    3012    DCA Z 12
1654    1365    TAD BFRTAB+12
1655    3015    DCA Z 15
1656    1367    TAD BFRTAB+14
1657    3014    DCA Z 14
1660    4336    JMS M2
```

```
1661  1354  TAD BFRTAB+1
1662  3016  DCA Z 16
1663  1354  TAD BFRTAB+1
1664  3012  DCA Z 12
1665  1361  TAD BFRTAB+6
1666  3015  DCA Z 15
1667  1364  TAD BFRTAB+11
1670  3014  DCA Z 14
1671  4336  JMS M2
1672  1355  TAD BFRTAB+2
1673  3016  DCA Z 16
1674  1355  TAD BFRTAB+2
1675  3012  DCA Z 12
1676  1360  TAD BFRTAB+5
1677  3015  DCA Z 15
1700  1371  TAD BFRTAB+16
1701  3014  DCA Z 14
1702  4336  JMS M2
1703  6301  HOLD,CCL01
1704  1043  TAD Z DISDON
1705  7640  SZA CLA          /IS DISPLAY DONE?
1706  5304  JMP .-2          /NO, WAIT
1707  6302  SCL01            /YES
1710  1047  TAD Z FIRST      /IS THIS FIRST FRAME
1711  7640  SZA CLA
1712  5324  JMP .+12
1713  6351  SCL08
1714  1065  TAD Z NFRAME
1715  3045  DCA Z FRAME
1716  7240  CLA CMA
1717  3046  DCA Z TRIAD
1720  7001  IAC
1721  3047  DCA Z FIRST
1722  6452  CMR
1723  6402  AMC
1724  7604  LAS
1725  7510  SPA              /HALT?
1726  5175  JMP Z HALT
1727  7006  RTL
1730  7430  SZL              /HOLD FRAME?
1731  5303  JMP HOLD
1732  7710  SPA CLA          /OMIT UPDATE?
1733  7001  IAC
1734  3056  DCA Z OMINUP
1735  5514  JMP I Z PTHREE   /UPDATE POINTS
1736  0000  M2,0
1737  1350  TAD CN03
1740  3042  DCA Z COUNT
1741  1416  TAD I Z 16
1742  3415  DCA I Z 15
1743  1412  TAD I Z 12
1744  3414  DCA I Z 14
1745  2042  ISZ Z COUNT
1746  5341  JMP .-5
1747  5736  JMP I M2
1750  7775  CN03,-3
1751  7761  CN17,-17
1752  1752  PBFRTB,BFRTAB-1
1753  0000  BFRTAB,0
1754  0000  0
1755  0000  0
1756  0000  0
1757  0000  0
1760  0000  0
1761  0000  0
1762  0000  0
1763  0000  0
1764  0000  0
1765  0000  0
1766  0000  0
1767  0000  0
1770  0000  0
1771  0000  0
```

```
                /       DISPLAY ROUTINE

                *2000
2000    3057    UPDIS,DCA Z SAC     /SAVE CONTENTS OF AC
2001    7004    RAL
2002    3365    DCA SLINK           /SAVE LINK
2003    7501    MQA
2004    3366    DCA MQ              /SAVE CONTENTS OF MQ
2005    6454    CLIF                /CLEAR ANALOG FLAG
2006    6322    SCL04               /DRAW SOLID LINE
2007    1045    TAD Z FRAME         /GET LINE NUMBER
2010    1362    TAD C5
2011    7450    SNA                 /IS IT LINE 9?
2012    5220    JMP .+6
2013    7001    IAC
2014    7450    SNA                 /IS IT LINE 8?
2015    5220    JMP .+3
2016    1363    TAD C11
2017    7650    SNA CLA             /IS IT LINE 1?
2020    6321    CCL04               /DRAW DASHED LINE
2021    2045    ISZ Z FRAME         /END OF FRAME?
2022    7001    IAC
2023    3043    DCA Z DISDON        /DISDON=0 AT END OF FRAME
2024    2046    ISZ Z TRIAD         /NEW TRIAD?
2025    5246    JMP SLOPE           /IF NOT SET SLOPE
2026    6346    SETIC,CCL08 SCL07   /ES TO IC & REQ ADD INTERRUPT
                                    /AND IC HOLD TO SET MODE
2027    1417    TAD I Z 17          /LOAD D-A BUFFERS
2030    6552    DALB1
2031    7041    CIA
2032    3367    DCA XICCOM          /AND STORE NEG OF IC
2033    1417    TAD I Z 17
2034    6554    DALB2
2035    7041    CIA
2036    3370    DCA YICCOM
2037    1417    TAD I Z 17
2040    6332    CCL06               /UNBLANK
2041    7650    SNA CLA             /IF ZERO THEN BLANK
2042    6334    SCL06               /BLANK
2043    1364    TAD NTRIAD          /INTERRUPTS IN TRIAD
2044    3046    DCA Z TRIAD
2045    5316    JMP CVRTDA          /GO TO CONVERT D-A
2046    6341    SLOPE,CCL07         /IC HOLD TO HOLD MODE
2047    1417    TAD I Z 17
2050    1367    TAD XICCOM          /COMPUTE SLOPE
2051    6552    DALB1               /AND LOAD BUFFER
2052    4352    JMS SQ
2053    3371    DCA P1
2054    7501    MQA
2055    3372    DCA P2
2056    1417    TAD I Z 17
2057    1370    TAD YICCOM
```

```
2060  6554  DALB2
2061  4352  JMS SQ
2062  1371  TAD P1
2063  3371  DCA P1
2064  7100  CLL
2065  7501  MQA
2066  1372  TAD P2
2067  7421  MQL
2070  7004  RAL
2071  1371  TAD P1
2072  7450  SNA
2073  5344  JMP SMALL
2074  4507  JMS I Z PLOG
2075  7425  MQL MUY
2076  2525  PW1,2525
2077  3371  DCA P1
2100  7501  MQA
2101  7710  SPA CLA
2102  7001  IAC
2103  1371  TAD P1
2104  1375  TAD SCALE
2105  4776  JMS I PALOG
2106  1374  TAD C1000
2107  6562  DALB3
2110  7200  CLA
2111  1417  TAD I Z 17
2112  6324  CCL05             /UNBLANK
2113  7650  SNA CLA           /IF ZERO THEN BLANK
2114  6331  SCL05             /BLANK
2115  6351  SCL08             /ES TO SLOPE
2116  6551  CVRTDA,DALC1
2117  6561  DALC2
2120  1043  TAD Z DISDON
2121  7640  SZA CLA           /SET UP FOR NEW FRAME?
2122  5334  JMP .+12
2123  1065  TAD Z NFRAME      /INTERRUPTS IN FRAME
2124  3045  DCA Z FRAME
2125  1044  TAD Z PLIST       /START OF DISPLAY LIST-1
2126  3017  DCA Z 17
2127  1044  TAD Z PLIST
2130  1373  TAD C61
2131  3375  DCA SCALE       /CLA IF NO DEPTH
2132  1775  TAD I SCALE
2133  3375  DCA SCALE       /CLA IF NO DEPTH
2134  7300  CLA CLL
2135  1366  TAD MQ
2136  7421  MQL
2137  1365  TAD SLINK
2140  7010  RAR               /RESTORE LINK
2141  1057  TAD Z SAC         /RESTORE AC
2142  6001  ION               /INTERRUPT ON
2143  5400  JMP I Z 0         /RETURN
```

```
2144  4507  SMALL,JMS I Z PLOG
2145  7040  CMA
2146  7425  MQL MUY
2147  2525  PW1A,2525
2150  7041  CIA
2151  5277  JMP PW1+1

2152  0000  SQ,0
2153  7510  SPA
2154  7041  CIA
2155  3360  DCA .+3
2156  1360  TAD .+2
2157  7425  MQL MUY
2160  0000  0
2161  5752  JMP I SQ

2162  0005  C5,5
2163  0011  C11,11
2164  7774  NTRIAD,-4
2165  0000  SLINK,0
2166  0000  MQ,0
2167  0000  XICCOM,0
2170  0000  YICCOM,0
2171  0000  P1,0
2172  0000  P2,0
2173  0061  C61,61
2174  0600  C1000,600
2175  5024  SCALE,5024        /0525+5075-0576=5024 IF NO DEPTH
2176  6701  PALOG,6701
```

```
/  DOUBLE PRECISION MULTIPLY ROUTINE

            *2200
2200  0000  DPMUL,0
2201  7100  CLL
2202  7510  SPA
2203  7061  CML CIA
2204  3214  DCA MLTPL1
2205  1052  TAD Z HIGH
2206  7510  SPA
2207  5257  JMP COMP
2210  7421  MQL
2211  7004  RAL
2212  3267  DCA SIGN
2213  7405  BACK,MUY
2214  0000  MLTPL1,0
2215  3052  DCA Z HIGH
2216  7701  MQA CLA
2217  3270  DCA PL
2220  1214  TAD MLTPL1
2221  3224  DCA MLTPL2
2222  1053  TAD LOW
2223  7425  MQL MUY
2224  0000  MLTPL2,0
2225  1270  TAD PL
2226  3053  DCA Z LOW
2227  7004  RAL
2230  1052  TAD Z HIGH
2231  3052  DCA Z HIGH
2232  7701  MQA CLA
2233  3054  DCA Z LLOW
2234  1267  TAD SIGN
2235  7650  SNA CLA
2236  5254  JMP COMP-3
2237  1054  TAD Z LLOW
2240  7141  CLL CIA
2241  3054  DCA Z LLOW
2242  1053  TAD Z LOW
2243  7040  CMA
2244  7430  SZL
2245  7101  CLL IAC
2246  3053  DCA Z LOW
2247  1052  TAD Z HIGH
2250  7040  CMA
2251  7430  SZL
2252  7101  CLL IAC
2253  3052  DCA Z HIGH
2254  7100  CLL
2255  1054  TAD Z LLOW
2256  5600  JMP I DPMUL
2257  7060  COMP,CMA CML
2260  7421  MQL
2261  7004  RAL
2262  3267  DCA SIGN
2263  1053  TAD Z LOW
2264  7040  CMA
2265  3053  DCA Z LOW
2266  5213  JMP BACK
2267  0000  SIGN,0
2270  0000  PL,0
```

```
/  SINGLE PRECISION
/ MULTIPLY ROUTINE

2271  0000  MUL,0
2272  7100  CLL
2273  7510  SPA
2274  7061  CML CIA
2275  7421  MQL
2276  1055  TAD Z MPR
2277  7510  SPA
2300  7061  CML CIA
2301  3305  DCA MLTPLR
2302  7004  RAL
2303  3326  DCA SIGN1
2304  7405  MUY
2305  0000  MLTPLR,0
2306  3052  DCA Z HIGH
2307  1326  TAD SIGN1
2310  7010  RAR
2311  7701  MQA CLA
2312  7420  SNL
2313  5324  JMP LAST
2314  7141  CLL CIA
2315  3053  DCA Z LOW
2316  1052  TAD Z HIGH
2317  7040  CMA
2320  7430  SZL
2321  7001  IAC
2322  3052  DCA Z HIGH
2323  1053  TAD Z LOW
2324  7100  LAST,CLL
2325  5671  JMP I MUL
2326  0000  SIGN1,0
```

```
        / TRANSLATION SUBROUTINE

                *2400
2400    0000    TRANS,0
2401    7421    MQL
2402    1031    TAD Z DELX
2403    7415    ASR
2404    0006    0006
2405    3052    DCA Z HIGH
2406    7100    CLL
2407    7501    MQA
2410    1021    TAD Z XL
2411    3021    DCA Z XL
2412    7004    RAL
2413    1052    TAD Z HIGH
2414    1020    TAD Z XH
2415    3020    DCA Z XH
2416    7421    MQL
2417    1032    TAD Z DELY
2420    7415    ASR
2421    0006    0006
2422    3052    DCA Z HIGH
2423    7100    CLL
2424    7501    MQA
2425    1024    TAD Z YL
2426    3024    DCA Z YL
2427    7004    RAL
2430    1052    TAD Z HIGH
2431    1023    TAD Z YH
2432    3023    DCA Z YH
2433    7421    MQL
2434    1033    TAD Z DELZ
2435    7415    ASR
2436    0006    0006
2437    3052    DCA Z HIGH
2440    7100    CLL
2441    7501    MQA
2442    1027    TAD Z ZL
2443    3027    DCA Z ZL
2444    7004    RAL
2445    1052    TAD Z HIGH
2446    1026    TAD Z ZH
2447    3026    DCA Z ZH
2450    5600    JMP I TRANS
```

```
        / FRACTIONAL DIVISION ROUTINE

2451    0000    FRADIV,0
2452    7300    CLA CLL
2453    1020    TAD Z XH
2454    7510    SPA
2455    7061    CMA CML IAC
2456    3266    DCA DIVSOR
2457    7420    SNL
2460    7040    CMA
2461    7100    CLL
2462    3277    DCA SIGN2
2463    7421    MQL
2464    1061    TAD Z B
2465    7407    DVI
2466    0000    DIVSOR,0
2467    7701    MQA CLA
2470    7110    CLL RAR
2471    7430    SZL
2472    7001    IAC
2473    2277    ISZ SIGN2
2474    7041    CIA
2475    3040    DCA Z BOD
2476    5651    JMP I FRADIV
2477    0000    SIGN2,0
```

```
/  CALCULATION OF D**2

               *2600
2600   0000    DEPTH,0
2601   1020    TAD Z XH
2602   7041    CIA
2603   1061    TAD Z B
2604   7740    SMA SZA CLA
2605   5600    JMP I DEPTH
2606   1020    TAD Z XH
2607   4242    JMS SQ1
2610   3021    DCA Z XL
2611   7501    MQA
2612   3022    DCA Z XLL
2613   1023    TAD Z YH
2614   4242    JMS SQ1
2615   1021    TAD Z XL
2616   3021    DCA Z XL
2617   7100    CLL
2620   7501    MQA
2621   1022    TAD Z XLL
2622   3022    DCA Z XLL
2623   7430    SZL
2624   2021    ISZ Z XL
2625   1026    TAD Z ZH
2626   4242    JMS SQ1
2627   1021    TAD Z XL
2630   3021    DCA Z XL
2631   7100    CLL
2632   7501    MQA
2633   1022    TAD Z XLL
2634   7710    SPA CLA
2635   7001    IAC
2636   7430    SZL
2637   7001    IAC
2640   1021    TAD Z XL
2641   5600    JMP I DEPTH

2642   0000    SQ1,0
2643   7510    SPA
2644   7041    CIA
2645   3250    DCA .+3
2646   1250    TAD .+2
2647   7425    MQL MUY
2650   0000    0
2651   5642    JMP I SQ1
```

```
/  SUBROUTINE TO COMPUTE
/  DOT PRODUCT OF VECTORS

2652   0000    DTPROD,0
2653   1023    TAD Z PVX
2654   7041    CIA
2655   1026    TAD Z NVX
2656   3026    DCA Z NVX
2657   1037    TAD Z DELYHD
2660   1024    TAD Z PVY
2661   7041    CIA
2662   1027    TAD Z NVY
2663   3027    DCA Z NVY
2664   1025    TAD Z PVZ
2665   7041    CIA
2666   1030    TAD Z NVZ
2667   3030    DCA Z NVZ
2670   1026    TAD Z NVX
2671   3055    DCA Z MPR
2672   1023    TAD Z PVX
2673   4510    JMS I Z PMUL
2674   3021    DCA Z XL
2675   1052    TAD Z HIGH
2676   3020    DCA Z XH
2677   1027    TAD Z NVY
2700   3055    DCA Z MPR
2701   1024    TAD Z PVY
2702   4510    JMS I Z PMUL
2703   1021    TAD Z XL
2704   3021    DCA Z XL
2705   7004    RAL
2706   1052    TAD Z HIGH
2707   1020    TAD Z XH
2710   3020    DCA Z XH
2711   1030    TAD Z NVZ
2712   3055    DCA Z MPR
2713   1025    TAD Z PVZ
2714   4510    JMS I Z PMUL
2715   1021    TAD Z XL
2716   7204    CLA RAL
2717   1052    TAD Z HIGH
2720   1020    TAD Z XH
2721   7104    CLL RAL
2722   7204    CLA RAL
2723   5652    JMP I DTPROD
```

```
                *BUFER1
3110    0000    0    /H0
3111    0000    0    /V0
3112    0000    0    /D0
3113    0000    0    /H1
3114    0000    0    /V1
3115    0000    0    /D1
3116    0000    0    /H2
3117    0000    0    /V2
3120    0000    0    /D2
3121    0000    0    /H3
3122    0000    0    /V3
3123    0000    0    /D3
3124    0000    0    /H4
3125    0000    0    /V4
3126    0000    0    /D4
3127    0000    0    /H5
3130    0000    0    /V5
3131    0000    0    /D5
3132    0000    0    /H3    (H6)
3133    0000    0    /V3    (V6)
3134    0000    0    /D3    (D6)
3135    0000    0    /H2    (H7)
3136    0000    0    /V2    (V7)
3137    0000    0    /D2    (D7)
3140    0000    0    /H6
3141    0000    0    /V6
3142    0000    0    /D6
3143    0000    0    /H5
3144    0000    0    /V5
3145    0000    0    /D5
3146    0000    0    /H2
3147    0000    0    /V2
3150    0000    0    /D2
3151    0000    0    /H1
3152    0000    0    /V1
3153    0000    0    /D1
3154    0000    0    /H7
3155    0000    0    /V7
3156    0000    0    /D7
3157    0000    0    /H1
3160    0000    0    /V1
3161    0000    0    /D1
3162    0000    0    /H5
3163    0000    0    /V5
3164    0000    0    /D5
3165    0000    0    /H3
3166    0000    0    /V3
3167    0000    0    /D3
```

```
                *PRMIN
3200    1000    1000 /X0
3201    0000    0
3202    0000    0
3203    1040    1040    /X1
3204    0000    0
3205    0000    0
3206    1000    1000    /X2
3207    0000    0
3210    0000    0
3211    1000    1000    /X3
3212    0000    0
3213    0000    0
3214    1000    1000    /X4
3215    0000    0
3216    0000    0
3217    1040    1040    /X5
3220    0000    0
3221    0000    0
3222    1040    1040    /X6
3223    0000    0
3224    0000    0
3225    1040    1040    /X7
3226    0000    0
3227    0000    0
3230    7760    7760    /Y0
3231    0000    0
3232    0000    0
3233    7760    7760    /Y1
3234    0000    0
3235    0000    0
3236    0020    0020    /Y2
3237    0000    0
3240    0000    0
3241    7760    7760    /Y3
3242    0000    0
3243    0000    0
3244    0020    0020    /Y4
3245    0000    0
3246    0000    0
3247    0020    0020    /Y5
3250    0000    0
3251    0000    0
3252    0020    0020    /Y6
3253    0000    0
3254    0000    0
3255    7760    7760    /Y7
3256    0000    0
3257    0000    0
3260    7760    7760    /Z0
3261    0000    0
3262    0000    0
3263    7760    7760    /Z1
3264    0000    0
3265    0000    0
```

```
3266  7760  7760  /Z2
3267  0000  0
3270  0000  0
3271  0020  0020  /Z3
3272  0000  0
3273  0000  0
3274  0020  0020  /Z4
3275  0000  0
3276  0000  0
3277  0020  0020  /Z5
3300  0000  0
3301  0000  0
3302  7760  7760  /Z6
3303  0000  0
3304  0000  0
3305  0020  0020  /Z7
3306  0000  0
3307  0000  0
```

```
/   PROGRAM BY NOEL VAN HOUTTE -- MVCL
/   EVALUATION OF THE LOGARITHM
/   OF AN OCTAL NUMBER
/   SUBROUTINE FOR TABLE LOOK UP
/                        INTERPOLATION

         *6501

6501  0000  LOG,0
6502  7450  SNA
6503  7501  MQA
6504  7417  LSR
6505  0001  0001
6506  7411  NMI
6507  3373  DCA NORM
6510  3374  DCA EXPON
6511  7441  SCA
6512  7450  SNA
6513  5316  JMP .+3
6514  1375  TAD BREAK
6515  7500  SMA
6516  7402  HLT         /CHECK STOP
6517  1377  TAD C0003
6520  2374  ISZ EXPON
6521  7510  SPA
6522  5317  JMP .-3
6523  7450  SNA
6524  5333  JMP NO
6525  7110  CLL RAR
6526  3331  DCA SHIFT
6527  1373  TAD NORM
6530  7417  LSR
6531  0000  SHIFT,0
6532  3373  DCA NORM

6533  7240  NO,CLA CMA
6534  1374  TAD EXPON
6535  7110  CLL RAR
6536  7012  RTR
6537  3374  DCA EXPON /IF ARG WAS ONLY IN MQ,
6540  1373  TAD NORM  /LINK COMES ON
6541  7417  LSR
6542  0004  0004
6543  1372  TAD LOGTAB
6544  3357  DCA LOGLOC
6545  1757  TAD I LOGLOC
6546  3331  DCA A
6547  2357  ISZ LOGLOC
6550  1757  TAD I LOGLOC
6551  3357  DCA B
6552  1331  TAD A
6553  7041  CIA
6554  1357  TAD B
6555  3357  DCA MLTPLR
6556  7405  MUY
6557  0000  MLTPLR,0
6560  1331  TAD A
6561  7417  LSR
6562  0001  0001
6563  3373  DCA NORM
6564  7501  MQA
6565  1376  TAD CONS
6566  7204  CLA RAL
6567  1373  TAD NORM
6570  1374  TAD EXPON
6571  5701  JMP I LOG

6572  6400  LOGTAB,6400
6573  0000  NORM,0
6574  0000  EXPON,0
6575  7763  BREAK,-0015
6576  3777  CONS,3777
6577  0003  C0003,0003

            A=SHIFT
            B=MLTPLR
            LOGLOC=B

A         6531
B         6557
BREAK     6575
CONS      6576
C0003     6577
EXPON     6574
LOG       6501
LOGLOC    6557
LOGTAB    6572
MLTPLR    6557
NO        6533
NORM      6573
SHIFT     6531
```

```
/   PROGRAM BY NOEL VAN HOUTTF -- MVCL
/   LOG   TABLE  FOR  TABLE  LOOK  UP

/   NUMBER VARIES BETWEEN  1  AND  8
/                 IN STEPS OF  .125

*6410

/OCTO      /DECI      NUMBER

0000       /0000      1.000
0350       /0232      1.125
0670       /0440      1.250
1163       /0627      1.375
1437       /0799      1.500
1674       /0956      1.625
2116       /1102      1.750
2326       /1238      1.875

2525       /1365      2.000
2715       /1485      2.125
3075       /1597      2.250
3250       /1704      2.375
3415       /1805      2.500
3555       /1901      2.625
3711       /1993      2.750
4040       /2080      2.875

4164       /2164      3.000
4304       /2244      3.125
4422       /2322      3.250
4534       /2396      3.375
4644       /2468      3.500
4751       /2537      3.625
5054       /2604      3.750
5154       /2668      3.875

5253       /2731      4.000
5347       /2791      4.125
5442       /2850      4.250
5533       /2907      4.375
5623       /2963      4.500
5711       /3017      4.625
5775       /3069      4.750
6060       /3120      4.875

6142       /3170      5.000
6223       /3219      5.125
6302       /3266      5.250
6361       /3313      5.375
6436       /3358      5.500
6512       /3402      5.625
6566       /3446      5.750
6640       /3488      5.875

/OCTO      /DECI      NUMBER

6711       /3529      6.000
6762       /3570      6.125
7032       /3610      6.250
7101       /3649      6.375
7147       /3687      6.500
7215       /3725      6.625
7261       /3761      6.750
7325       /3797      6.875

7371       /3833      7.000
7434       /3868      7.125
7476       /3902      7.250
7540       /3936      7.375
7601       /3969      7.500
7641       /4001      7.625
7701       /4033      7.750
7741       /4065      7.875

0000       /4096      8.000
```

```
/  PROGRAM BY NOEL VAN HOUTTE -- MVCL
/  EVALUATION OF THE ANTILOGARITHM
/  OF AN OCTAL NUMBER
/  SUBROUTINE FOR TABLE LOOK UP
/                     INTERPOLATION

*6701

6701  0000  ALOG,0
6702  3361  DCA LOG
6703  1361  TAD LOG
6704  0365  AND C6000
6705  7104  CLL RAL
6706  7006  RTL
6707  3362  DCA EXPON
6710  1361  TAD LOG
6711  0364  AND C1777
6712  7417  LSR
6713  0003  0003
6714  1360  TAD ALOTAB
6715  3330  DCA ALOLOC
6716  1730  TAD I ALOLOC
6717  3351  DCA A
6720  2330  ISZ ALOLOC
6721  1730  TAD I ALOLOC
6722  3330  DCA B
6723  1351  TAD A
6724  7041  CIA
6725  1330  TAD B
6726  3330  DCA MLTPLR
6727  7405  MUY
6730  0000  MLTPLR,0
6731  1351  TAD A
6732  3361  DCA NUMB
6733  7346  CLA CLL CMA RTL
6734  1362  TAD EXPON
6735  7041  CIA
6736  3351  DCA SHIFT
6737  1351  TAD SHIFT
6740  7650  SNA CLA
6741  5353  JMP NO
6742  1351  TAD SHIFT
6743  7104  CLL RAL
6744  1351  TAD SHIFT
6745  1363  TAD M0001
6746  3351  DCA SHIFT
6747  1361  TAD NUMB
6750  7417  LSR
6751  0000  SHIFT,0
6752  3361  DCA NUMB

6753  7501  NO,MQA
6754  7710  SPA CLA
6755  7001  IAC
6756  1361  TAD NUMB
6757  5701  JMP I ALOG

6760  6600  ALOTAB,6600
6761  0000  LOG,0
6762  0000  EXPON,0
6763  7777  M0001,-0001
6764  1777  C1777,1777
6765  6000  C6000,6000

A=SHIFT
B=MLTPLR
ALOLOC=B
NUMB=LOG
```

A	6751
ALOG	6701
ALOLOC	6730
ALOTAB	6760
B	6730
C1777	6764
C6000	6765
EXPON	6762
LOG	6761
MLTPLR	6730
M0001	6763
NO	6753
NUMB	6761
SHIFT	6751

```
/   PROGRAM BY NOEL VAN HOUTTE -- MVCL
/   ALOG  TABLE  FOR  TABLE  LOOK  UP

/   LOGARITHM VARIES BETWEEN  0  AND  1
/                     IN STEPS OF  .015625

*6600

/OCTO      /DECI       LOGARITHM

1000       /0512       0.000000
1021       /0529       0.015625
1042       /0546       0.031250
1064       /0564       0.046875
1107       /0583       0.062500
1132       /0602       0.078125
1156       /0622       0.093750
1203       /0643       0.109375

1230       /0664       0.125000
1256       /0686       0.140625
1305       /0709       0.156250
1334       /0732       0.171875
1364       /0756       0.187500
1415       /0781       0.203125
1447       /0807       0.218750
1502       /0834       0.234375

1535       /0861       0.250000
1572       /0890       0.265625
1627       /0919       0.281250
1665       /0949       0.296875
1725       /0981       0.312500
1765       /1013       0.328125
2026       /1046       0.343750
2071       /1081       0.359375

2135       /1117       0.375000
2202       /1154       0.390625
2250       /1192       0.406250
2317       /1231       0.421875
2370       /1272       0.437500
2442       /1314       0.453125
2515       /1357       0.468750
2572       /1402       0.484375

2650       /1448       0.500000
2730       /1496       0.515625
3011       /1545       0.531250
3075       /1596+1     0.546875
3161       /1649       0.562500
3250       /1704       0.578125
3340       /1760       0.593750
3432       /1818       0.609375

/OCTO      /DECI       LOGARITHM

3526       /1878       0.625000
3624       /1940       0.640625
3724       /2004       0.656250
4026       /2070       0.671875
4133       /2139       0.687500
4241       /2209       0.703125
4352       /2282       0.718750
4466       /2358       0.734375

4604       /2435+1     0.750000
4724       /2516       0.765625
5047       /2599       0.781250
5175       /2685       0.796875
5326       /2774       0.812500
5461       /2865       0.828125
5620       /2960       0.843750
5762       /3057+1     0.859375

6126       /3158       0.875000
6277       /3263       0.890625
6452       /3371-1     0.906250
6632       /3482       0.921875
7015       /3597       0.937500
7204       /3716       0.953125
7376       /3838       0.968750
7575       /3965       0.984375

0000       /4096       1.000000
```

APPENDIX B

M.I.T. INSTRUMENTATION LABORATORY HEAD POSITION MONITOR

The contact analog 3-D Display System (Appendix A) used for this thesis implements the equations of linear perspective from the position of the observer's eye. The equations using the three linear coordinates of eye position and a discussion of perspective are in Chapter 1. The position of a "cyclops" at the midpoint of the line between the subject's eyes was used in the equations. This position will be referred to as the observer's head position.

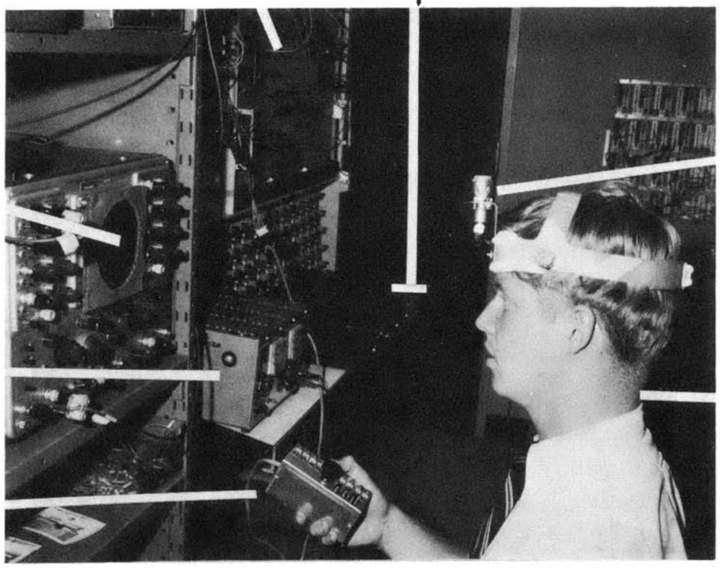
A method of monitoring the observer's head position was necessary to provide the head coordinates used in the perspective equations. It is required that the monitoring system be simple, accurate, and low noise while not encumbering the observer's head. Ultrasonic and photo-optical sensors were both considered for a head position monitor and a photo-optical system was selected for use with the PDP-8--GPS290T hybrid computer.

The M.I.T. Lincoln Laboratory has developed and built a three dimensional position sensor that uses ultrasonic pulses. The device is called the "Lincoln Wand"[10] and is used for computer graphics applications. The author spent a summer at the M.I.T. Lincoln Laboratory, under the supervision of William R. Sutherland, using the Lincoln Wand and TX-2 computer for preliminary investigation of displays implementing perspective with head movement. The Lincoln Wand has an array of four ultrasonic transmitters mounted in the plane of the CRT display screen. The receiver is mounted on a head band worn by the observer and does not encumber the observer's head movements. The head coordinates are calculated by the digital computer from the transmission delays from each of the four transmitters to the receiver. The system is very accurate, but is relatively complex and costly compared to a photo-optic system. The main reason that the Lincoln Wand was not duplicated for use with the PDP-8--GPS290T hybrid computer was the additional computation required to obtain the coordinates from the transmission delays.

The M.I.T. Man-Vehicle Control Laboratory worked on the development of a different ultrasonic head position monitoring system[14]. The system used a receiver at each end of three polystyrene rods and a transmitter attached to a head band worn by the observer. This configuration made each coordinate proportional to the difference in the arrival time of the transmitted ultrasonic pulse at each end of its corresponding rod. The system did not achieve the required accuracy (±0.5 cm) as a result of problems with acoustic reflections from the rod-receiver interface, transmitter beam pattern, and noise.

The single-axis prototype head position monitoring system, used with the PDP-8--GPS290T hybrid computer, was designed and built by George Davidson and Harold Seward under the supervision of Philip Bowditch, all members of the staff at the M.I.T. Instrumentation Laboratory. This photo-optic system was used to measure the lateral (left-right) horizontal position of the observer's head. The system consisted of a light source mounted on a head band worn by the subject, Figure B.1, and the Head Position Monitor suspended 90 inches above the subject's eye level, Figure B.2. The light source throws a rectangular patch of light on two photocells in the Head Position Monitor which give an output voltage proportional to the position of the light.

The light source used was a G-E 1631-X bulb. It was operated at 6.75 volts and 2.1 amperes by an Electro Products Laboratories model D-612T filtered D-C power supply. The bulb was partially covered with aluminum foil so that light would be emitted only in the upward direction. Because of the large physical size of the bulb-socket combination and the bulb's heat output, it was necessary to mount the bulb about 6 inches above the midpoint of the line between the subject's eyes. This meant that there was an undesirable lever arm which caused the bulb to move farther than the "clyclops" when the subject tilted his head to either side. A smaller and more efficient light bulb having the same light



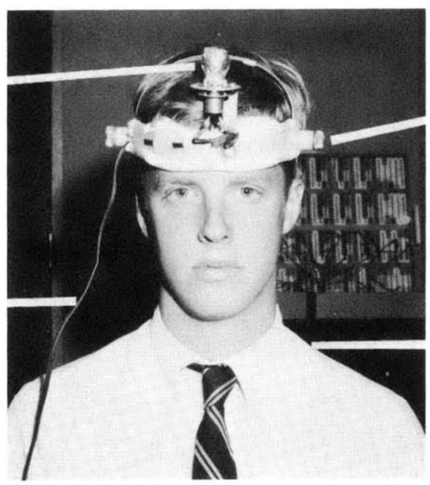


FIGURE B.1 THE SUBJECT WITH HEAD BAND
AND LIGHT BULB

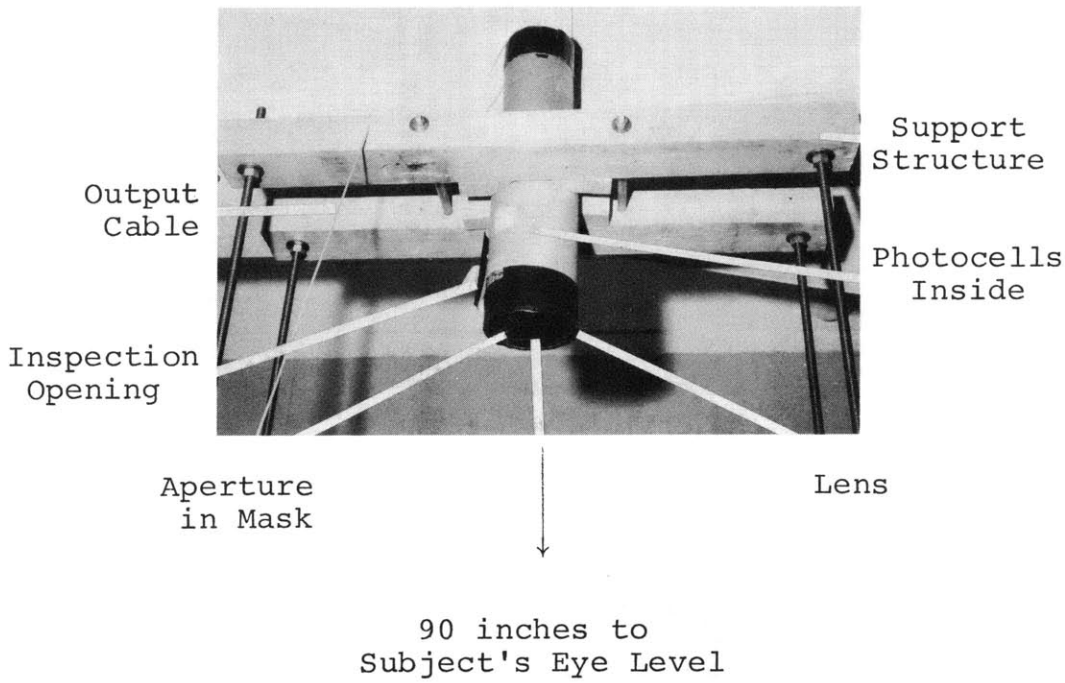


FIGURE B.2 THE HEAD POSITION MONITOR

output was desirable so that the lever arm could be reduced, but such a bulb was not found.

The Head Position Monitor has two photocells mounted behind a lens. The photocells are mounted side by side at one end of a tube. The silicon barrier junction photocells are 1 cm wide by 2 cm high. They are wired in reverse series so that the Head Position Monitor output is the difference between the voltages across each photocell. The lens is mounted at one end of a tube concentric to the one that supports the photocells. The use of concentric tubes allows the lens to photocell distance to be easily adjusted. The Head Position Monitor was used with the photocells 3 inches behind the lens. The lens is 3 1/2 inches in diameter with a 10 inch focal length. The lens is masked to leave a 3/8 by 13/16 inch aperture centered on the lens. The outer tube has an inspection opening for use during alignment.

The output of the Head Position Monitor is amplified before being applied to the analog to digital converter channel 7 which is the head position input for the 3-D Display System. The necessary D-C gain was obtained using amplifiers on the analog patch board. The interconnections for the Head Position Monitor amplifier are shown in Figure B.3. The D-C gain used (with the pot set at .309) was 1.24×10^3. The overall gain of the Head Position Monitor-amplifier system from light bulb position to AD7 is 1 volt/cm. This gain was specified so that the digital gain from the A-D conversion through the perspective calculation to CRT screen position

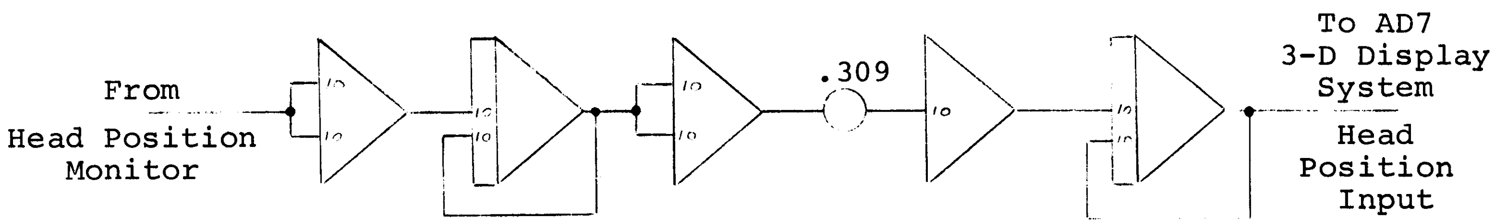


FIGURE B.3 THE HEAD POSITION MONITOR AMPLIFIER INTERCONNECTIONS

ON THE ANALOG PATCH BOARD

would be unity. This minimized jitter of the image on the screen caused by A-D conversion noise. Because both the amplifiers and the A-D converter saturate at ±10 volts, monitored head position is correct only between ±10 cm. The two cascaded first order lags, with time constant $\tau = 0.1$ seconds, are necessary to remove large amplitude, high frequency noise resulting from the cascaded amplifiers. In addition, the cascaded lags remove the fluorescent light noise component which is present in the output of the Head Position Monitor.

The calibration chart for amplifier output voltage at AD7 versus bulb position is shown in Table B.1. The calibration test was performed with the Head Position Monitor in its final position 84 inches above the bulb and with all parameters of the Head Position Monitor and amplifier as given above. The prototype Head Position Monitor as used measured the position of the bulb with an error not exceeding 0.45 cm for an accuracy of 4.5 percent of full scale. The output of the amplifier at AD7 was observed on an oscilloscope to determine the noise level. The noise level did not exceed 0.08 volts peak to peak. This is equivalent to a precision of 0.08 cm.

The photocells are mounted side by side in the same plane as shown in the diagram of Figure B.4. The plane of the photocells is parallel to the axis along which the coordinate is measured. The L axis is perpendicular to the split

Bulb Position cm	Amplifier Output Volts	Bulb Position cm	Amplifier Output Volts
+10	+10.45	-10	-10.38
+ 9	+ 9.35	- 9	- 9.15
+ 8	+ 8.19	- 8	- 8.01
+ 7	+ 7.10	- 7	- 6.90
+ 6	+ 6.05	- 6	- 5.90
+ 5	+ 4.99	- 5	- 4.90
+ 4	+ 3.82	- 4	- 3.94
+ 3	+ 2.80	- 3	- 2.90
+ 2	+ 1.85	- 2	- 1.95
+ 1	+ 0.93	- 1	- 0.95
0	0.00		

TABLE B.1 CALIBRATION CHART FOR HEAD POSITION MONITOR

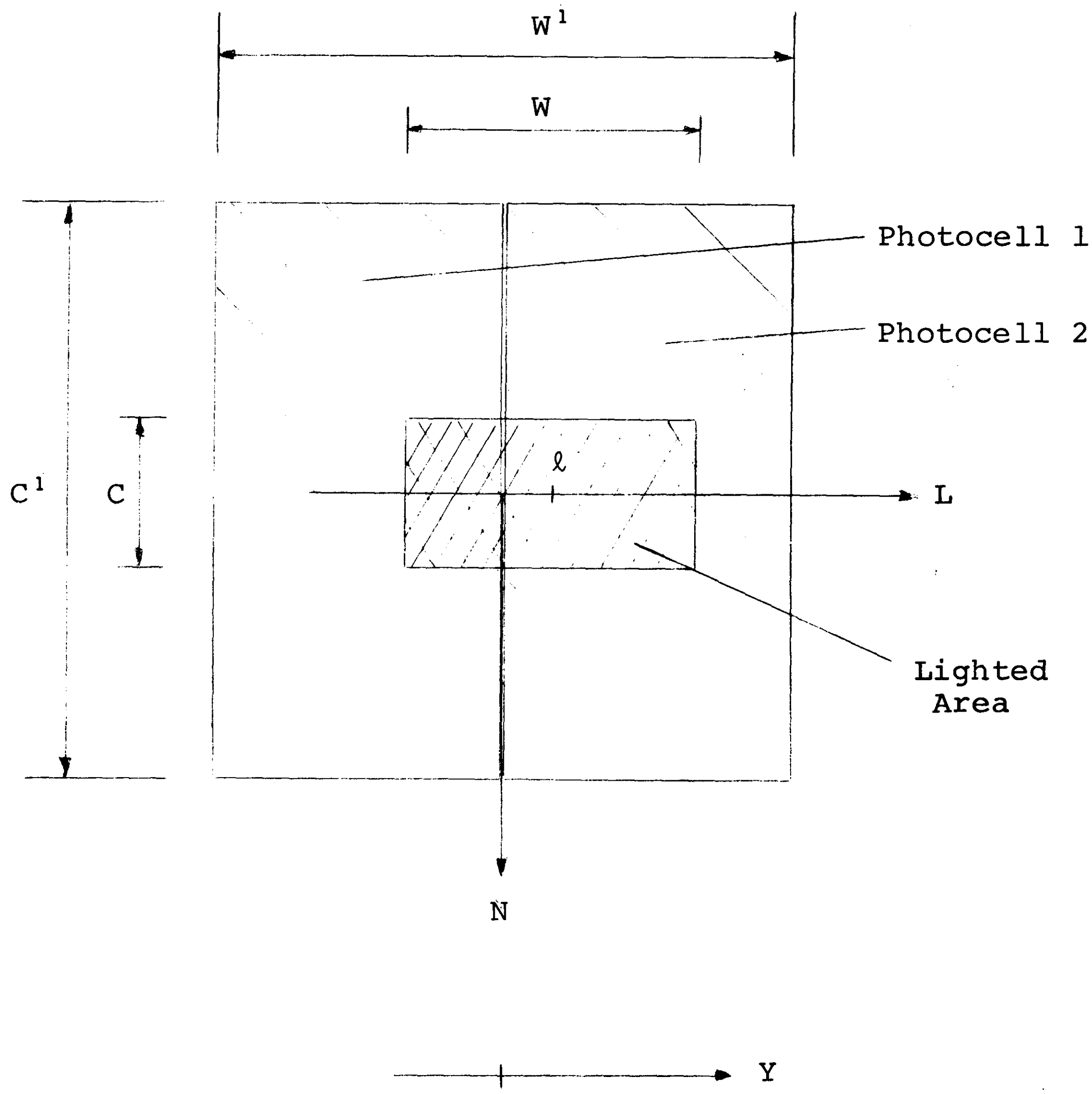


FIGURE B.4 SCHEMATIC DRAWING OF PHOTOCELL ARRANGEMENT between the photocells, and coplanar with the axis being measured. The crosshatched area represents the lighted area resulting from the rectangular aperture in the mask over the lens.

The output of the reverse series wired photocells was a voltage, that is, a high input impedance amplifier was used. The voltage output of each photocell is approximately proportional to the intensity of the light falling on it, I, times the lighted area A

$$V = V_2 - V_1 = k_2 \; I \; A_2 - k_1 \; I \; A_1$$

where V is the output voltage of the Head Position Monitor, V_1, V_2 are the voltages across each photocell, and k_1, k_2 are the proportionality constants for each photocell. The total lighted area remains constant, with width W and height C constant, as long as the angle $\alpha = \tan^{-1} \frac{y_{hd}}{G}$ is small. y_{hd} is the lateral displacement of the light bulb and G is the distance from the lens to the bulb. Thus,

$$V = k_2 \; I \; C(\frac{W}{2} + \ell) - k_1 \; I \; C(\frac{W}{2} - \ell)$$

where ℓ is the coordinate of the center of the lighted area. If the photocells are selected so that $k_2 = k_1 = k$, then

$$V = 2 \; k \; I \; C \; \ell$$

The optical properties of the lens yield

$$\frac{y_{hd}}{G} = - \frac{\ell}{E}$$

where E is the distance between lens and photocells.

Thus

$$V = - \frac{2\ k\ I\ C\ E}{G}\ y_{hd}$$

so that the output voltage, V, of the Head Position Monitor is directly proportional to the lateral displacement of the light bulb.

It is advantageous to have the gain 2 k I C E/G as large as possible so that less external amplifier gain will be required, and the system will be less noisy. This is achieved by using sensitive photocells and a light bulb with as much light output as practical. The remaining factors, mask size, lens-photocell and lens-bulb distances are interrelated. They are also influenced by photocell size, lens diameter and the lens focal length. They are also subject to constraints.

The Head Position Monitor is insensitive to position along the N axis, that is, perpendicular to the measurement axis when the lighted area does not extend above the top or below the bottom of the photocells. The constraint is

$$n + \frac{C}{2} \leq \frac{C^1}{2}$$

The photocell departs from linearity when the lighted area no longer falls on both photocells and when part of it falls beyond the right or left edge of the photocells. The constraints are

$$W \leq \frac{W^1}{2}$$

$$\ell_{max} + \frac{W}{2} \leq \frac{W^1}{2}$$

Since ℓ is proportional to the displacement, ℓ_{max} should be as large as possible. This leads to

$$\frac{E}{G} (y_{hd})_{max} = \frac{W^1}{4}$$

where E, the mask width, and lens focal length are such that

$$W = \frac{W^1}{2}$$

G is constrained by the requirement that $\tan^{-1} \frac{(y_{hd})_{max}}{G}$ be a small angle.

APPENDIX C

INTENSITY TESTING PROGRAM

For the Intensity Testing Program, the 3-D Display System was modified so that only two lines were displayed. The reference line was constant length and intensity and the other line was variable length and intensity. (See Chapter 2 for the parameters used in the experiment.) In the experiment, a subject was asked to adjust the amplitude of the intensification signal so that the variable length line had the same apparent brightness as the reference line. The Intensity Testing Program automatically selects the length of the variable line, displays the two lines, and records the intensification amplitude selected by the subject. At the end of the experiment, the program computes several statistical parameters of the intensification amplitudes and prints the amplitudes and statistics obtained at each line length.

The display circuitry on the analog and control patch boards is basically the same as for the 3-D Display System, shown in Figures A.6 to A.8. The analog patch board intensification circuitry was modified as shown in Figure C.1.

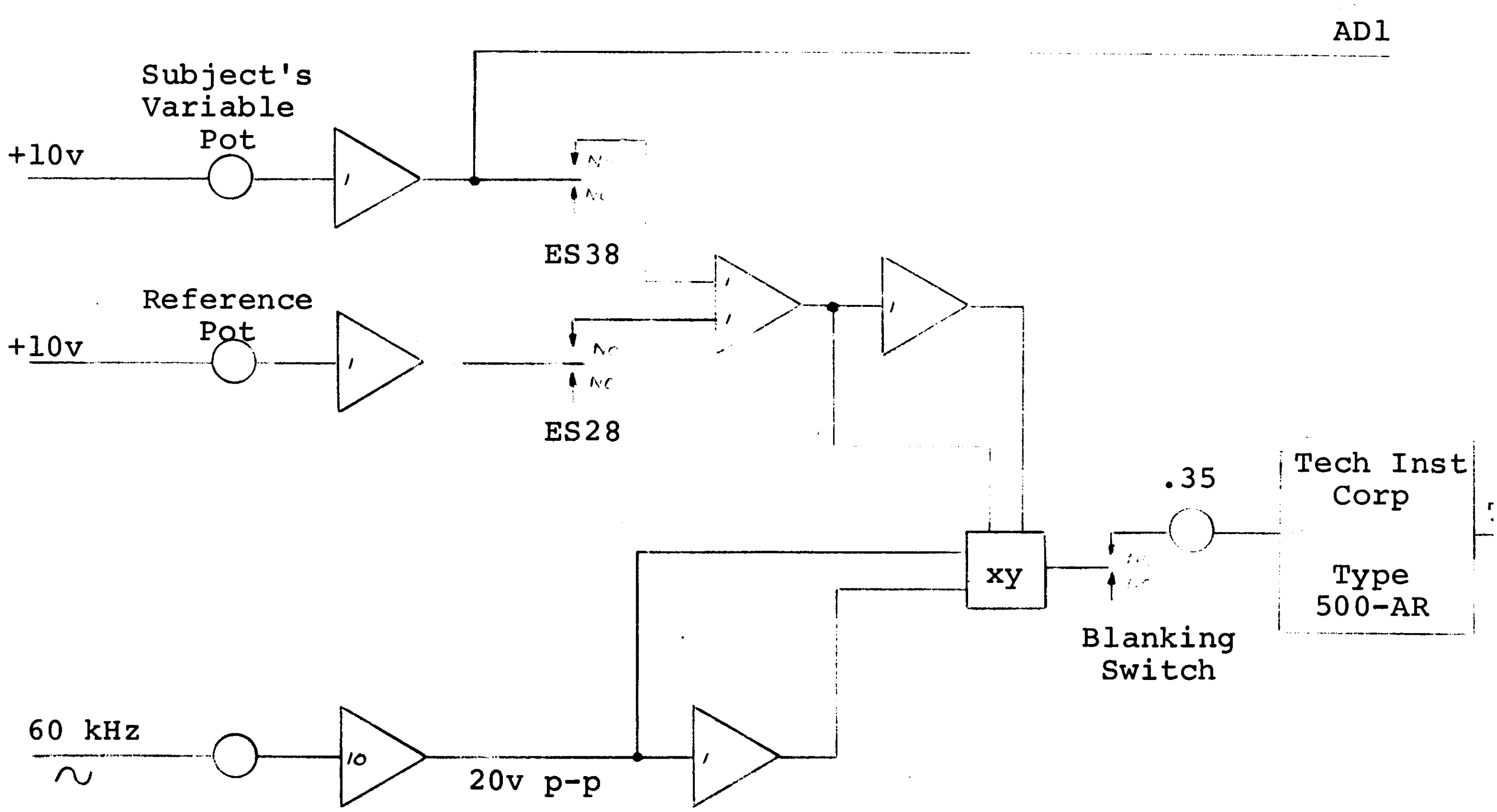


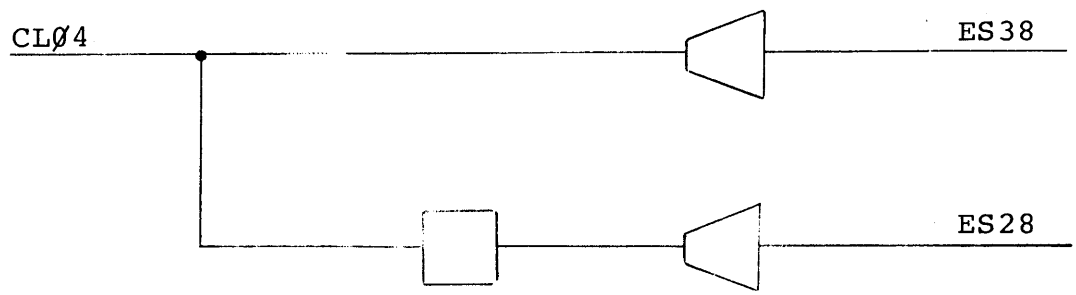
FIGURE C.1 REPLACEMENT ANALOG INTENSIFICATION CIRCUIT

Modifications to the control patch board logic circuit are shown in Figure C.2. The symbols for the logic elements are as shown in Figure A.7.

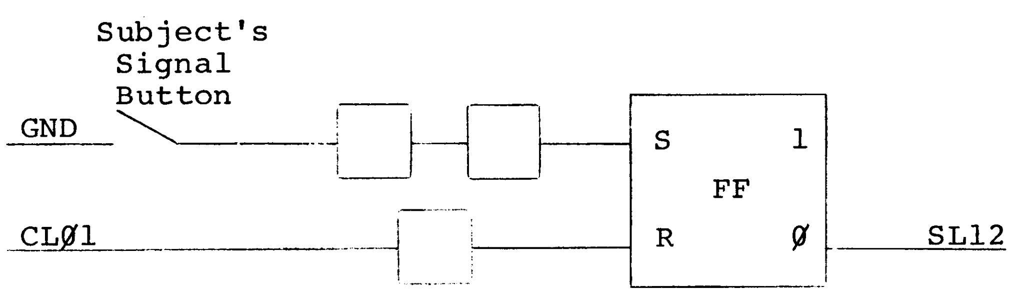
Based on the line dotting signal, CLØ4, the line is intensified either with the variable amplitude controlled by the subject or by a constant reference amplitude. CLØ4 at -3 volts corresponds to the variable length line with variable intensification under subject control.

When the subject signals that his intensity adjustment is complete, the flip-flop is set. The Ø output of the flip-flop grounds SL12 which results in accumulator bit 12 being 1 when the sense lines are read by the digital program. The digital program generates a -3 volt pulse on CLØ1 to reset the flip-flop.

The flow diagram for the portion of the digital program that presents the line lengths is shown in Figure C.3. The flow diagram for the statistical analysis of the amplitudes and printing of data points is shown in Figure C.4. The octal number next to a block indicates its location in PDP-8 core memory. The interrupt flow diagram has only minor modifications from Figures A.11.a to A.11.c and is not presented. Those modifications are: (1) the A-D converter servicing routine is just a return to the main program at 0270_8, (2) the display routine does not compute A(L,D), and (3) the criterion for blanking is D<Ø.



(Replacement for Line Dotting Logic)



(Additions)

FIGURE C.2 MODIFICATIONS TO CONTROL BOARD INTERCONNECTIONS FOR INTENSITY TESTING PROGRAM

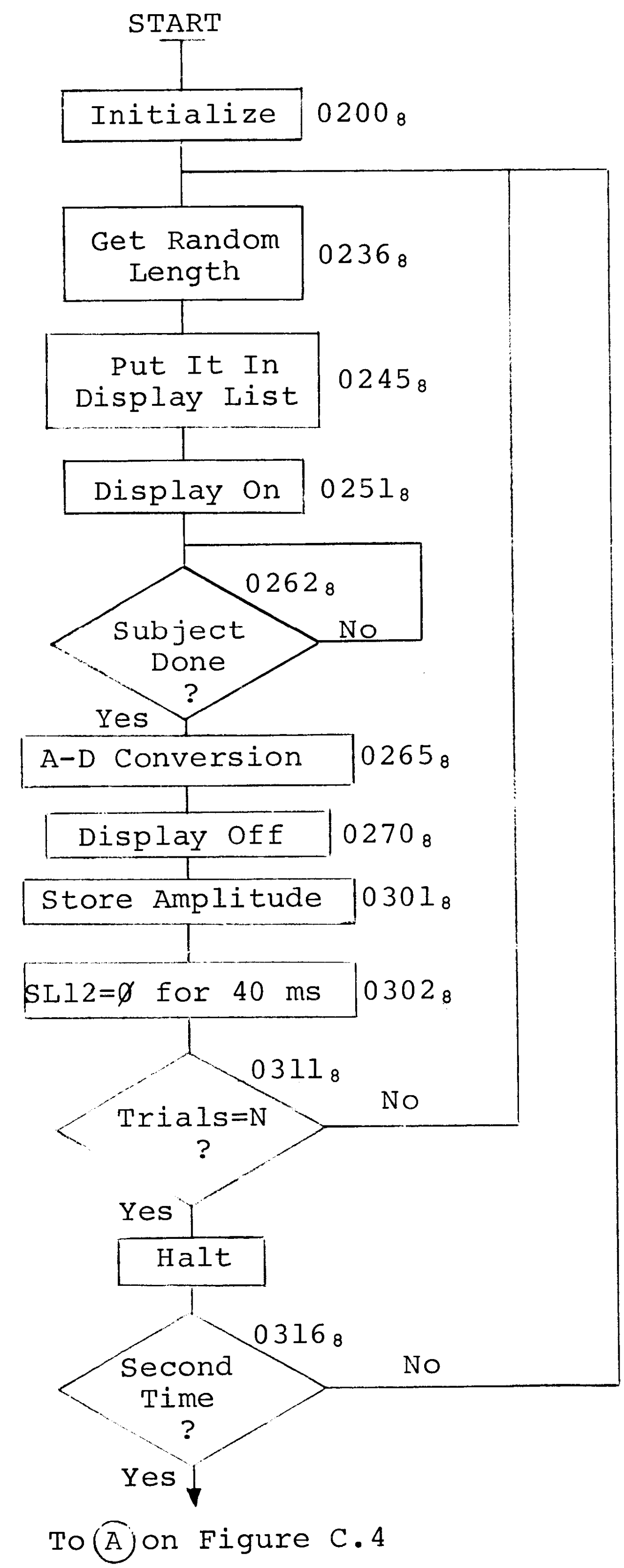


FIGURE C.3 FLOW DIAGRAM FOR FIRST SECTION OF INTENSITY TESTING PROGRAM

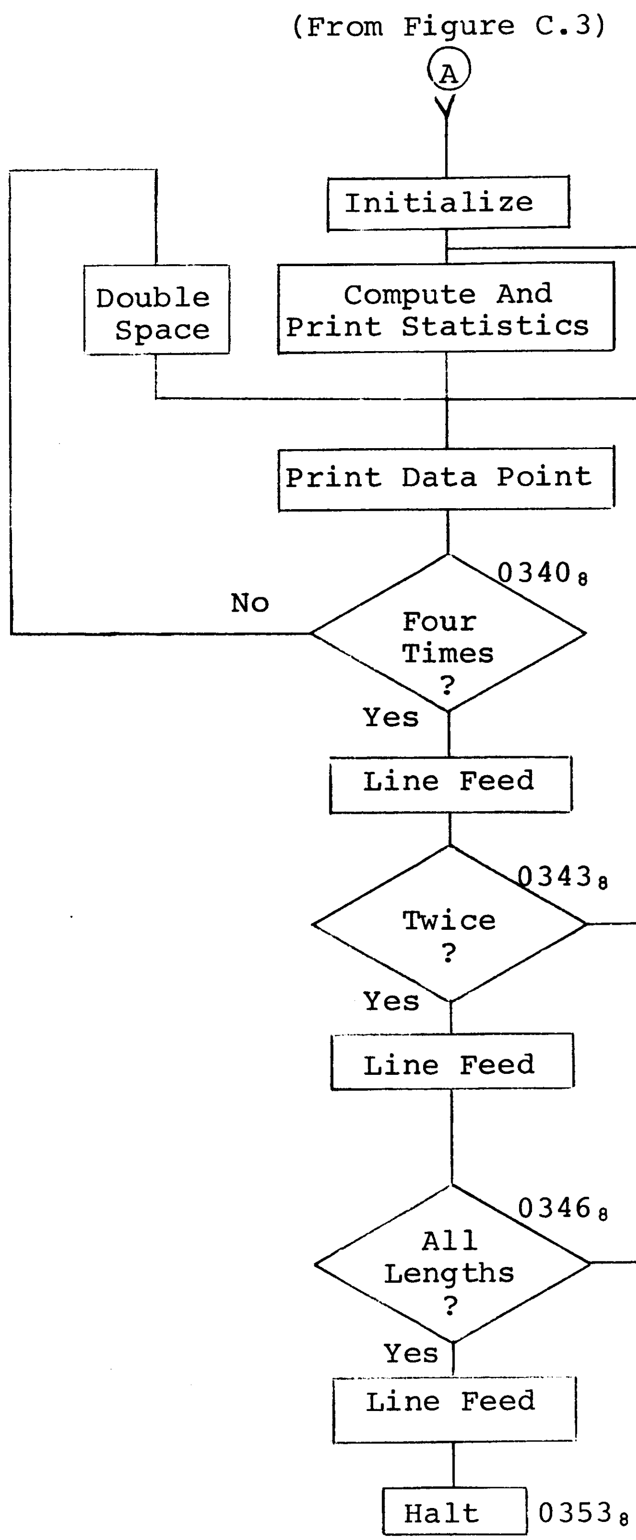


FIGURE C.4 FLOW DIAGRAM FOR SECOND SECTION OF INTENSTIY TESTING PROGRAM

The presentation order is specified by the table of pseudo-random (uncorrelated) length identification numbers. This table is TAB4 located at 1436_8. CPNEXT is the constant pointer to the start of TAB4 used to initialize PNEXT. The length ID number is obtained from the table via the variable pointer, PNEXT, and added to LNTHST, the constant pointer to the start of TAB3. The result is a pointer to the corresponding entry in the table of half lengths, TAB3 located at 1304_8.

The positive and negative of the half length are placed in the display list via CPLACE and SPLACE. There is only one display list (1200_8) and only the two locations (PLACE1 and PLACE2) specifying the horizontal screen coordinates of the end points of the variable length line are changed during program operation. This program uses an early version of the display routine (1000_8) which blanks for negative D entries in the display list. The D values were selected so that one solid and one "dotted" line were shown. The distinction, "dotted line," was not used by this program to actually dot the line. Rather the dotted line signal (CLØ4) is used to apply either the constant reference or subject controlled variable amplitude to the intensity signal while the corresponding line is being drawn. The DA3 intensity output is not used by this program.

The intensification amplitudes selected by the subject are stored in matrix form. A table of variable pointers, TAB2 (located at 1272_8 and pointed to by STOTAB), is initialized from TAB1 (located at 1260_8 and pointed to by PTOTAB). TAB1 is a table of constant pointers to the start of the amplitude storage area for each line length. The length ID number is added to STOTAB to obtain the pointer to the location of the pointer in TAB2. The amplitude is stored in the amplitude table, ANSTAB (1316_8), via the pointer obtained from TAB2. The pointer in TAB2 is incremented so that the amplitude resulting from the next presentation of that line length is stored in the next sequential location in ANSTAB.

PUPDIS, PSRAD, DISDON, PLIST, FRAME, TRIAD, SAC, and NFRAME are the same as used in the 3-D Display System described in Appendix A.

PDBLSP	points to the double space subroutine
PCRLF	points to the carriage return-line feed subroutine
PSCALE	points to the subroutine that scales a voltage for conversion from binary to decimal
PINBCD	points to the binary to decimal conversion subroutine
PUTOUT	points the subroutine to print the decimal number
PPRINT	points to the subroutine that prints the voltage
PANLZE	points to the routine to compute and print the statistics of the amplitudes

The trials are counted by TRIALS which is initialized to NTRIALS, minus one-half the total number of trials. COUNT is set to -2 in order to produce two sets of NTRIALS with a halt between them to allow changing the subject's instructions. CN4 is equal to -4 and specifies minus the number of times each line length occurs in NTRIALS. It is used to format the output and in the computation of statistics.

The subroutine ANLIZE computes the statistics of the intensity amplitudes selected by the subject. Each line length occurred four times in the first half of the experiment during which the subject was asked to decrease line intensity monotonically to equal brightness. Each line length occurred four times in the second half during which the subject was asked to increase intensity. The statistical computations make use of the knowledge that each line length occurs four times in each half and eight times in the total number of trials in order to perform the required divisions by shifting. For numbers other than 4 and 8, divisions executed during the computation of the averages must be programmed. The statistics computed at each line length are the average of the first four amplitudes HIAVE; the average of the second four amplitudes, LOAVE; the average of all eight, Grand Ave; the maximum, MAX; and the minimum, MIN. ACH and ACL are the simulated double precision accumulator. The averaging section is looped through once to compute HIAVE and again for LOAVE. The output format is

Line Length   HIAVE   LOAVE   Grand Ave   MAX   MIN where the line length is in centimeters and the other numbers are voltages. All numbers printed out are decimal. After the statistics are computed and printed, each amplitude is printed in order (four on a line). The format is

$$\begin{matrix} A_1 & A_2 & A_3 & A_4 \\ A_5 & A_6 & A_7 & A_8 \end{matrix}$$

The three lines of printout are produced for each line length. NLINES is minus the number of line lengths.

The subroutine SCALE is entered with the argument in the AC. The teletype code for the sign is placed in SIGN. MINUS is the teletype code for the minus sign and PLUS is the teletype code for the plus sign. The magnitude of the binary number is then scaled by $\frac{10.00}{20.48}$ so that the binary to decimal conversion will result in the correct decimal voltage. The result is left in the AC.

The subroutine BINBCD converts the binary number in the AC to decimal. BCD1 is the tens digit of the voltage, BCD2 the units, BCD3 the tenths, and BCD4 the hundredths. The constant 260_8 is added to get the teletype code.

The table of the octal core locations corresponding to symbolic names appears on page 145. The pass three listing of the Intensity Testing Program in PAL-III assembly language appears on pages 146 to 154.

A	0504
ACH	0074
ACL	0075
AD	0270
ANLIZE	0600
ANSTAB	1316
BCD	0460
BCD1	0514
BCD2	0515
BCD3	0516
BCD4	0517
BIN	0513
BINBCD	0435
CNTR	0521
CN2	0526
CN20	0527
CN3	0512
CN4	0055
CN43	0530
CN46	0531
COMPMA	0630
COMPMI	0637
CONTNU	0646
COR	0462
COUNT	0060
COVRT	0452
CPHIAV	0066
CPLACE	0044
CPNEXT	0043
CRLF	0556
CVRTDA	1074
C11	1114
C2	0511
C260	0532
C5	1113
DBLSP	0564
DISDON	0032
FRAME	0034
HIAVE	0070
HOLDS	0064
INIT1	0507
INIT2	0510
LIST	1200
LNTHST	0040
LOAVE	0071
LOOP	0225
LOOP1	0212
LOOP2	0326
LOOP3	0331
LOOP4	0334
LOOP5	0621
LOOP6	0615
MAX	0072
MIN	0073
MINUS	0523
NEXT	0465
NFRAME	0037
NLINES	0054
NTRIAD	1115
NTRIAL	0053
NXTTRY	0236
OTHER	0020
OUTPUT	0542
PANLZE	0076
PCRLF	0047
PDBLSP	0046
PHIAVE	0067
PINBCD	0051
PLACE1	1230
PLACE2	1233
PLIST	0033
PLUS	0524
PNEXT	0056
PNR	0061
PNS	0062
PPRINT	0065
PRINT	0572
PSCALE	0050
PSRAD	0031
PTOTAB	0042
PUPDIS	0030
PUTOUT	0052
SAC	0036
SCALE	0400
SETIC	1030
SIGN	0522
SLINK	1116
SLOPE	1054
SPLACE	0045
START	0200
STO	0525
STOTAB	0041
TAB1	1260
TAB2	1272
TAB3	1304
TAB4	1436
TEMP	0520
TRIAD	0035
TRIALS	0057
TYPE	0533
UPDIS	1000
WHICH	0063
XICCOM	1117
YICCOM	1120
ZICCOM	1121

```
                *1
0001   6461     SKIF
0002   5430     JMP I PUPDIS
0003   6451     ADNF
0004   5431     JMP I PSRAD
0005   5020     JMP OTHER

                *20
0020   3036     OTHER,DCA SAC
0021   6036     KRB
0022   6042     TCF
0023   6772     MMCF
0024   7200     CLA
0025   1036     TAD SAC
0026   6001     ION
0027   5400     JMP I 0

0030   1000     PUPDIS,UPDIS
0031   0270     PSRAD,AD
0032   0000     DISDON,0
0033   1177     PLIST,LIST-1
0034   0000     FRAME,0
0035   0000     TRIAD,0
0036   0000     SAC,0
0037   7760     NFRAME,-20
0040   1304     LNTHST,TAB3
0041   1272     STOTAB,TAB2
0042   1260     PTOTAB,TAB1
0043   1436     CPNEXT,TAB4
0044   1230     CPLACE,PLACE1
0045   1233     SPLACE,PLACE2
0046   0564     PDBLSP,DBLSP
0047   0556     PCRLF,CRLF
0050   0400     PSCALE,SCALE
0051   0435     PINBCD,BINBCD
0052   0542     PUTOUT,OUTPUT
0053   7730     NTRIALS,-50
0054   7766     NLINES,-12
0055   7774     CN4,-4
0056   0000     PNEXT,0
0057   0000     TRIALS,0
0060   0000     COUNT,0
0061   0000     PNR,0
0062   0000     PNS,0
0063   0000     WHICH,0
0064   0000     HOLDS,0
0065   0572     PPRINT,PRINT
0066   0070     CPHIAV,HIAVE
0067   0000     PHIAVE,0
0070   0000     HIAVE,0
0071   0000     LOAVE,0
0072   0000     MAX,0
0073   0000     MIN,0
0074   0000     ACH,0
0075   0000     ACL,0
0076   0600     PANLZE,ANLIZE

                *200
0200   1043     START,TAD CPNEXT
0201   3056     DCA PNEXT
0202   1053     TAD NTRIALS
0203   3057     DCA TRIALS
0204   1054     TAD NLINES
0205   3060     DCA COUNT
0206   1041     TAD STOTAB
0207   3061     DCA PNR
0210   1042     TAD PTOTAB
0211   3062     DCA PNS
0212   1462     LOOP1,TAD I PNS
0213   3461     DCA I PNR
0214   2061     ISZ PNR
0215   2062     ISZ PNS
0216   2060     ISZ COUNT
0217   5212     JMP LOOP1
0220   1442     TAD I PTOTAB
0221   3061     DCA PNR
0222   1053     TAD NTRIALS
0223   7104     CLL RAL
0224   3060     DCA COUNT
0225   3461     LOOP,DCA I PNR
0226   2061     ISZ PNR
0227   2060     ISZ COUNT
0230   5225     JMP LOOP
0231   7344     CLA CLL CMA RAL
0232   3060     DCA COUNT
0233   6545     ADCC ADIC
0234   6303     CCL01 SCL01
0235   7402     HLT

0236   1456     NXTTRY,TAD I PNEXT
0237   2056     ISZ PNEXT
0240   3063     DCA WHICH
0241   1063     TAD WHICH
0242   1040     TAD LNTHST
0243   3061     DCA PNR
0244   1461     TAD I PNR
0245   3444     DCA I CPLACE
0246   1444     TAD I CPLACE
0247   7041     CIA
0250   3445     DCA I SPLACE
0251   6351     SCL08
0252   1037     TAD NFRAME
0253   3034     DCA FRAME
```

```
0254   7240   CLA CMA
0255   3035   DCA TRIAD
0256   6452   CMR
0257   6402   AMC
0260   6001   ION
0261   6303   CCL01 SCL01
0262   6435   CAC SLR
0263   7650   SNA CLA
0264   5262   JMP .-2
0265   6532   ADCV
0266   7300   CLA CLL
0267   5266   JMP .-1

0270   6452   AD,CMR
0271   6404   AMPS
0272   1063   TAD WHICH
0273   1041   TAD STOTAB
0274   3061   DCA PNR
0275   1461   TAD I PNR
0276   2461   ISZ I PNR
0277   3061   DCA PNR
0300   6534   ADRB
0301   3461   DCA I PNR
0302   3064   DCA HOLDS
0303   6303   CCL01 SCL01
0304   6435   CAC SLR
0305   7640   SZA CLA
0306   5302   JMP .-4
0307   2064   ISZ HOLDS
0310   5304   JMP .-4
0311   2057   ISZ TRIALS
0312   5236   JMP NXTTRY
0313   1053   TAD NTRIAL
0314   3057   DCA TRIALS
0315   7402   HLT
0316   2060   ISZ COUNT
0317   5236   JMP NXTTRY

0320   1442   TAD I PTOTAB
0321   3056   DCA PNEXT
0322   1054   TAD NLINES
0323   3060   DCA COUNT
0324   1040   TAD LNTHST
0325   3063   DCA WHICH
0326   7344   LOOP2,CLA CLL CMA RAL
0327   3061   DCA PNR
0330   4476   JMS I PANLZE
0331   1055   LOOP3,TAD CN4
0332   3062   DCA PNS
0333   7410   SKP
0334   4446   LOOP4,JMS I PDBLSP
0335   1456   TAD I PNEXT
0336   2056   ISZ PNEXT
0337   4465   JMS I PPRINT
0340   2062   ISZ PNS
0341   5334   JMP LOOP4
0342   4447   JMS I PCRLF
0343   2061   ISZ PNR
0344   5331   JMP LOOP3
0345   4447   JMS I PCRLF
0346   2060   ISZ COUNT
0347   5326   JMP LOOP2
0350   4447   JMS I PCRLF
0351   4447   JMS I PCRLF
0352   7402   HLT
0353   5200   JMP START
```

```
               *400
0400   0000    SCALE,0
0401   3313    DCA BIN
0402   1313    TAD BIN
0403   7700    SMA CLA
0404   5213    JMP .+7
0405   1323    TAD MINUS
0406   3322    DCA SIGN
0407   1313    TAD BIN
0410   7041    CIA
0411   3313    DCA BIN
0412   5215    JMP .+3
0413   1324    TAD PLUS
0414   3322    DCA SIGN
0415   1313    TAD BIN
0416   7110    CLL RAR
0417   3313    DCA BIN
0420   1313    TAD BIN
0421   7415    ASR
0422   0004    4
0423   3325    DCA STO
0424   1325    TAD STO
0425   7041    CIA
0426   1313    TAD BIN
0427   3313    DCA BIN
0430   1325    TAD STO
0431   7110    CLL RAR
0432   7110    CLL RAR
0433   1313    TAD BIN
0434   5600    JMP I SCALE

0435   0000    BINBCD,0
0436   3313    DCA BIN
0437   3314    DCA BCD1
0440   3315    DCA BCD2
0441   3316    DCA BCD3
0442   3317    DCA BCD4
0443   1312    TAD CN3
0444   3321    DCA CNTR
0445   1307    TAD INIT1
0446   3252    DCA COVRT
0447   1310    TAD INIT2
0450   3260    DCA BCD
0451   7100    CLL
0452   1304    COVRT,TAD A
0453   1313    TAD BIN
0454   7510    SPA
0455   5265    JMP NEXT
0456   3313    DCA BIN
0457   7100    CLL
0460   2314    BCD,ISZ BCD1
0461   5252    JMP COVRT
0462   7100    COR,CLL
0463   1320    TAD TEMP
0464   5256    JMP .-6
0465   3320    NEXT,DCA TEMP
0466   1321    TAD CNTR
0467   0311    AND C2
0470   7440    SZA
0471   5274    JMP .+3
0472   7430    SZL
0473   5262    JMP COR
0474   7300    CLA CLL
0475   2252    ISZ COVRT
0476   2260    ISZ BCD
0477   2321    ISZ CNTR
0500   5252    JMP COVRT
0501   1313    TAD BIN
0502   3317    DCA BCD4
0503   5635    JMP I BINBCD

0504   6030    A,6030
0505   7634    7634
0506   7766    7766
0507   1304    INIT1,TAD A
0510   2314    INIT2,ISZ BCD1
0511   0002    C2,2
0512   7775    CN3,-3
0513   0000    BIN,0
0514   0000    BCD1,0
0515   0000    BCD2,0
0516   0000    BCD3,0
0517   0000    BCD4,0
0520   0000    TEMP,0
0521   0000    CNTR,0
0522   0000    SIGN,0
0523   7775    MINUS,255-260
0524   7773    PLUS,253-260
0525   0000    STO,0
0526   7776    CN2,-2
0527   7760    CN20,-20
0530   7735    CN43,-43
0531   7732    CN46,-46
0532   0260    C260,260

0533   0000    TYPE,0
0534   1332    TAD C260
0535   6046    TLS
0536   6041    TSF
0537   5336    JMP .-1
0540   7200    CLA
0541   5733    JMP I TYPE
```

```
0542  0000  OUTPUT,0
0543  1314  TAD BCD1
0544  4333  JMS TYPE
0545  1315  TAD BCD2
0546  4333  JMS TYPE
0547  1326  TAD CN2
0550  4333  JMS TYPE
0551  1316  TAD BCD3
0552  4333  JMS TYPE
0553  1317  TAD BCD4
0554  4333  JMS TYPE
0555  5742  JMP I OUTPUT

0556  0000  CRLF,0
0557  1330  TAD CN43
0560  4333  JMS TYPE
0561  1331  TAD CN46
0562  4333  JMS TYPE
0563  5756  JMP I CRLF

0564  0000  DBLSP,0
0565  1327  TAD CN20
0566  4333  JMS TYPE
0567  1327  TAD CN20
0570  4333  JMS TYPE
0571  5764  JMP I DBLSP

0572  0000  PRINT,0
0573  4450  JMS I PSCALE
0574  4451  JMS I PINBCD
0575  4452  JMS I PUTOUT
0576  5772  JMP I PRINT
```

```
                *600
0600    0000    ANLIZE,0
0601    1463    TAD I WHICH
0602    2063    ISZ WHICH
0603    7041    CIA
0604    7104    CLL RAL
0605    4465    JMS I PPRINT
0606    1056    TAD PNEXT
0607    3057    DCA TRIALS
0610    3072    DCA MAX
0611    7150    CLL CMA RAR
0612    3073    DCA MIN
0613    1066    TAD CPHIAV
0614    3067    DCA PHIAVE
0615    1055    LOOP6,TAD CN4
0616    3062    DCA PNS
0617    3074    DCA ACH
0620    3075    DCA ACL
0621    1457    LOOP5,TAD I TRIALS
0622    7141    CLL CIA
0623    1075    TAD ACL
0624    3075    DCA ACL
0625    7004    RAL
0626    1074    TAD ACH
0627    3074    DCA ACH
0630    1457    COMPMAX,TAD I TRIALS
0631    1072    TAD MAX
0632    7700    SMA CLA
0633    5237    JMP COMPMIN
0634    1457    TAD I TRIALS
0635    7041    CIA
0636    3072    DCA MAX
0637    1457    COMPMIN,TAD I TRIALS
0640    1073    TAD MIN
0641    7750    SPA SNA CLA
0642    5246    JMP CONTNU
0643    1457    TAD I TRIALS
0644    7041    CIA
0645    3073    DCA MIN
0646    2057    CONTNU,ISZ TRIALS
0647    2062    ISZ PNS
0650    5221    JMP LOOP5
0651    1075    TAD ACL
0652    7421    MQL
0653    1074    TAD ACH
0654    7415    ASR
0655    0001    1
0656    7701    MQA CLA
0657    3467    DCA I PHIAVE
0660    4446    JMS I PDBLSP
0661    1467    TAD I PHIAVE
0662    4465    JMS I PPRINT
0663    2067    ISZ PHIAVE
0664    2061    ISZ PNR
0665    5215    JMP LOOP6
0666    7344    CLA CLL CMA RAL
0667    3061    DCA PNR
0670    4446    JMS I PDBLSP
0671    1070    TAD HIAVE
0672    1071    TAD LOAVE
0673    7110    CLL RAR
0674    4465    JMS I PPRINT
0675    4446    JMS I PDBLSP
0676    1072    TAD MAX
0677    4465    JMS I PPRINT
0700    4446    JMS I PDBLSP
0701    1073    TAD MIN
0702    4465    JMS I PPRINT
0703    4447    JMS I PCRLF
0704    5600    JMP I ANLIZE
```

```
                /       DISPLAY ROUTINE

                *1000
1000    3036    UPDIS,DCA Z SAC     /SAVE CONTENTS OF AC
1001    7004    RAL
1002    3316    DCA SLINK           /SAVE LINK
1003    7001    IAC
1004    3032    DCA Z DISDON
1005    6454    CLIF                /CLEAR ANALOG FLAG
1006    1034    TAD Z FRAME         /GET LINE NUMBER
1007    1313    TAD C5
1010    7450    SNA                 /IS IT LINE 9?
1011    5222    JMP .+11
1012    7001    IAC
1013    7450    SNA                 /IS IT LINE 8?
1014    5222    JMP .+6
1015    1314    TAD C11
1016    7650    SNA CLA             /IS IT LINE 1?
1017    5222    JMP .+3
1020    6322    SCL04               /DRAW SOLID LINE
1021    7410    SKP
1022    6321    CCL04               /DRAW DASHED LINE
1023    2034    ISZ Z FRAME         /END OF FRAME?
1024    7410    SKP
1025    3032    DCA Z DISDON        /DISDON=0 AT END OF FRAME
1026    2035    ISZ Z TRIAD         /NEW TRIAD?
1027    5254    JMP SLOPE           /IF NOT SET SLOPE
1030    6344    SETIC,CCL08         /ES TO IC & REQ ADD INTERRUPT
1031    6342    SCL07               /IC HOLD TO SET MODE
1032    1417    TAD I Z 17          /LOAD D-A BUFFERS
1033    6552    DALB1
1034    7041    CIA
1035    3317    DCA XICCOM          /AND STORE NEG OF IC
1036    1417    TAD I Z 17
1037    6554    DALB2
1040    7041    CIA
1041    3320    DCA YICCOM
1042    1417    TAD I Z 17
1043    6332    CCL06
1044    7510    SPA
1045    6334    SCL06
1046    6562    DALB3
1047    7041    CIA
1050    3321    DCA ZICCOM
1051    1315    TAD NTRIAD          /INTERRUPTS IN TRIAD
1052    3035    DCA Z TRIAD
1053    5274    JMP CVRTDA          /GO TO CONVERT D-A
1054    6341    SLOPE,CCL07         /IC HOLD TO HOLD MODE
1055    1417    TAD I Z 17
1056    1317    TAD XICCOM          /COMPUTE SLOPE
1057    6552    DALB1               /AND LOAD BUFFER
1060    7200    CLA
```

```
1061  1417  TAD I Z 17
1062  1320  TAD YICCOM
1063  6554  DALB2
1064  7200  CLA
1065  1417  TAD I Z 17
1066  6324  CCL05
1067  7510  SPA
1070  6331  SCL05
1071  1321  TAD ZICCOM
1072  6562  DALB3
1073  6351  SCL08                /ES TO SLOPE
1074  6551  CVRTDA,DALC1
1075  6561  DALC2
1076  7300  CLA CLL
1077  1032  TAD Z DISDON
1100  7640  SZA CLA              /SET UP FOR NEW FRAME?
1101  5306  JMP .+5
1102  1037  TAD Z NFRAME         /INTERRUPTS IN FRAME
1103  3034  DCA Z FRAME
1104  1033  TAD Z PLIST          /START OF DISPLAY LIST-1
1105  3017  DCA Z 17
1106  1316  TAD SLINK
1107  7010  RAR                  /RESTORE LINK
1110  1036  TAD Z SAC            /RESTORE AC
1111  6001  ION                  /INTERRUPT ON
1112  5400  JMP I Z 0            /RETURN
1113  0005  C5,5
1114  0011  C11,11
1115  7774  NTRIAD,-4
1116  0000  SLINK,0
1117  0000  XICCOM,0
1120  0000  YICCOM,0
1121  0000  ZICCOM,0
```

```
                *1200
1200    7000    LIST,7000
1201    7740    7740
1202    1777    1777
1203    1000    1000
1204    7740    7740
1205    1777    1777
1206    0000    0
1207    0000    0
1210    7000    7000
1211    0000    0
1212    0000    0
1213    7000    7000
1214    0000    0
1215    0000    0
1216    7000    7000
1217    0000    0
1220    0000    0
1221    0000    0
1222    0000    0
1223    0000    0
1224    0000    0
1225    0000    0
1226    0000    0
1227    0000    0
1230    7400    PLACE1,7400
1231    0040    0040
1232    1777    1777
1233    0400    PLACE2,400
1234    0040    0040
1235    1777    1777
1236    0000    0
1237    0000    0
1240    7000    7000
1241    0000    0
1242    0000    0
1243    7000    7000
1244    0000    0
1245    0000    0
1246    7000    7000
1247    0000    0
1250    0000    0
1251    0000    0
1252    0000    0
1253    0000    0
1254    0000    0
1255    0000    0
1256    0000    0
1257    0000    0

1260    1316    TAB1,ANSTAB
1261    1326    ANSTAB+10
1262    1336    ANSTAB+20
1263    1346    ANSTAB+30
1264    1356    ANSTAB+40
1265    1366    ANSTAB+50
1266    1376    ANSTAB+60
1267    1406    ANSTAB+70
1270    1416    ANSTAB+100
1271    1426    ANSTAB+110

1272    0000    TAB2,0
1273    0000    0
1274    0000    0
1275    0000    0
1276    0000    0
1277    0000    0
1300    0000    0
1301    0000    0
1302    0000    0
1303    0000    0

1304    7770    TAB3,7770
1305    7750    7750
1306    7700    7700
1307    7600    7600
1310    7500    7500
1311    7400    7400
1312    7300    7300
1313    7200    7200
1314    7100    7100
1315    7000    7000

1316    0000    ANSTAB,0
```

```
                *ANSTAB+120
1436    0002    TAB4,2
1437    0004    4
1440    0010    10
1441    0006    6
1442    0003    3
1443    0002    2
1444    0000    0
1445    0005    5
1446    0001    1
1447    0007    7
1450    0011    11
1451    0006    6
1452    0004    4
1453    0007    7
1454    0000    0
1455    0003    3
1456    0011    11
1457    0010    10
1460    0005    5
1461    0003    3
1462    0001    1
1463    0002    2
1464    0006    6
1465    0007    7
1466    0002    2
1467    0011    11
1470    0001    1
1471    0004    4
1472    0003    3
1473    0010    10
1474    0007    7
1475    0005    5
1476    0006    6
1477    0000    0
1500    0004    4
1501    0005    5
1502    0011    11
1503    0000    0
1504    0001    1
1505    0010    10
1506    0002    2
1507    0010    10
1510    0001    1
1511    0000    0
1512    0011    11
1513    0005    5
1514    0004    4
1515    0000    0
1516    0006    6
1517    0005    5
1520    0007    7
1521    0010    10
1522    0003    3
1523    0004    4
1524    0001    1
1525    0011    11
1526    0002    2
1527    0007    7
1530    0006    6
1531    0002    2
1532    0001    1
1533    0003    3
1534    0005    5
1535    0010    10
1536    0011    11
1537    0003    3
1540    0000    0
1541    0007    7
1542    0004    4
1543    0006    6
1544    0011    11
1545    0007    7
1546    0001    1
1547    0005    5
1550    0000    0
1551    0002    2
1552    0003    3
1553    0006    6
1554    0010    10
1555    0004    4
```

APPENDIX D

DEPTH TESTING PROGRAM

The Depth Testing Program is a program to be loaded over the 3-D Display System described in Appendix A. That is, both programs reside in PDP-8 core at the same time, and each does a portion of the job of running the experiment. The Depth Testing Program is used to change the variable inertial list of the 3-D Display System so that the cube is positioned at one of a series of discrete positions, or depths, along the X axis (as in Appendix A). The subject in the experiment is asked to identify the depth and press the button corresponding to that depth. The program detects the button selection and stores (n_{ij}), the number of times that the j-th button was selected in response to the i-th depth, in matrix form.

At the conclusion of the experiment the program prints the stimulus-response matrix. The format of the output is as in Table 4.3 except that the column and row headings are not printed. Decimal numbers are printed for n_{ij}. Leader and trailer are outputted so that the matrix may be simultaneously punched. The resulting paper tape is compatible with, and used for input to, the PDP-8 Fortran programs used to evaluate the information transmission and correlation coefficient of the matrix. These Fortran programs are described in Appendix E.

Each button produces its corresponding binary number at the control board. This is accomplished in the "button box" by using multiple OR gates implemented with diodes as shown schematically in Figure D.1. The additional control board interconnections for the buttons are shown schematically in Figure D.2, with the logic symbols as defined in Figure A.7. The inputs of the flip-flops are sensitive to small amplitude positive going transients. Crosstalk in the cable from the button box to the control board caused such transients in button lines that should have been quiescent. An inverter functions as a level detector because the input must reach a threshold for switching to occur. Therefore, each button line is filtered by a double inversion to remove crosstalk noise and not have an inverted signal. The bit lines from the button box set corresponding flip-flops, whose Ø outputs ground sense lines so that the correct binary number is read into the accumulator by the program. The program generates a -3 volt pulse on CLØ3 to reset the flip-flops. Otherwise the control board logic is as shown in Figure A.8.

The analog patch board interconnections are identical to those shown in Figure A.6.

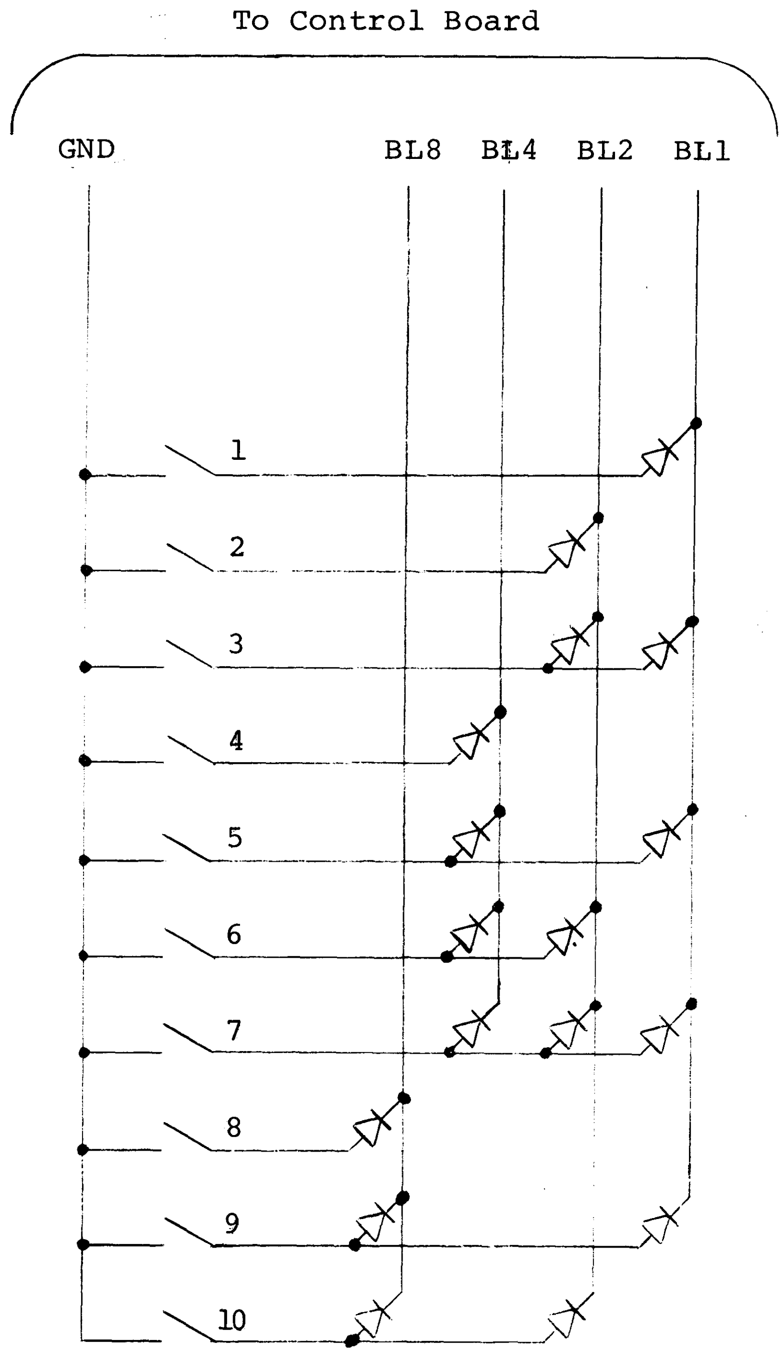
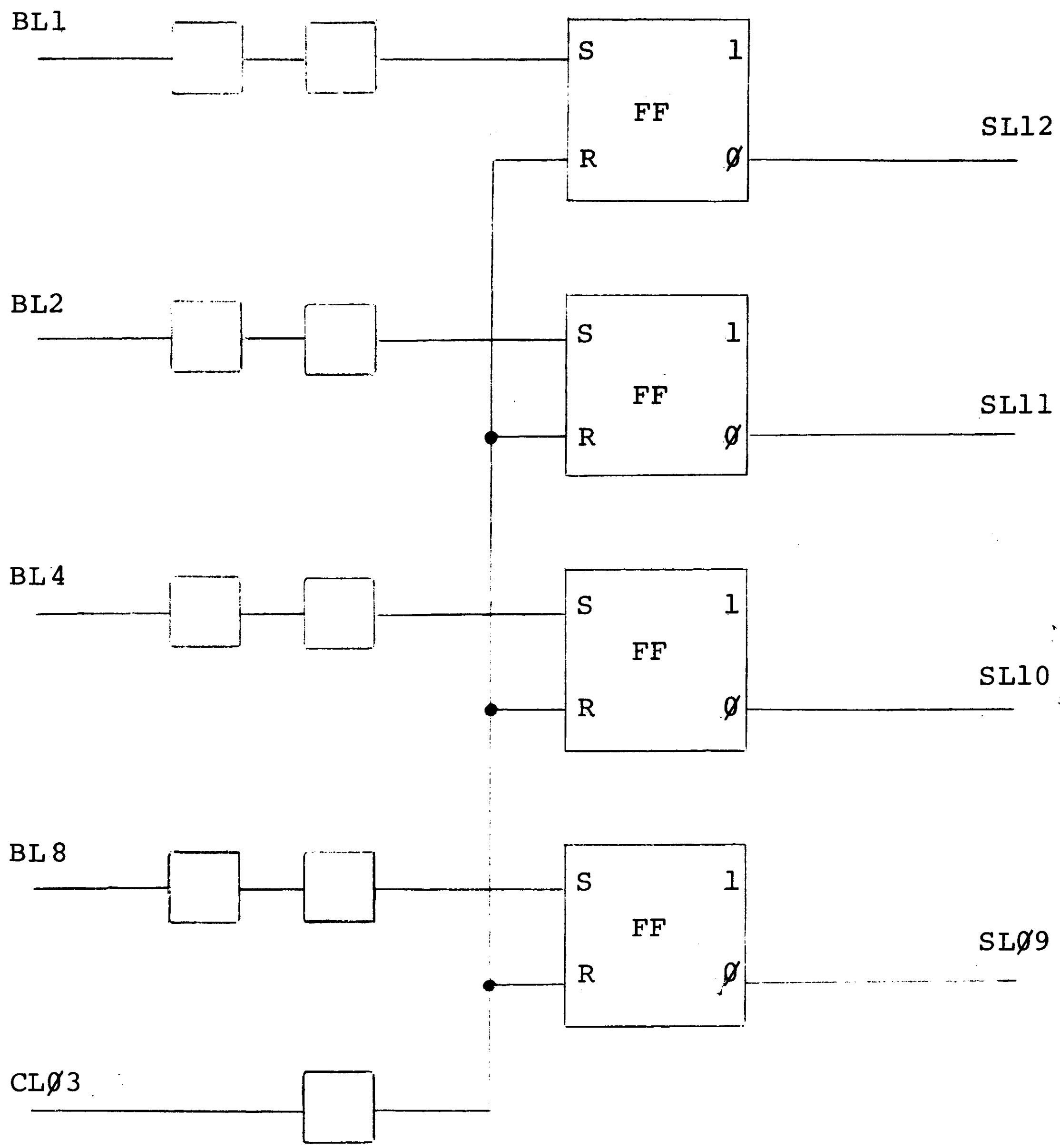


FIGURE D.1 SCHEMATIC OF MULTIPLE OR GATES
IN "BUTTON BOX"



BLn = bit line n from "button box"

FIGURE D.2 ADDITIONS TO CONTROL BOARD INTERCONNECTIONS

The flow diagrams for the 3-D Display System, Figures A.10.a to A.10.c and A.11.a to A.11.c, are applicable. They are referred to by the flow diagrams in this appendix. Keep in mind that OMINUP=1 at all times to prevent the 3-D Display System from updating the variable inertial list. Also the display-off, halt, and initialization section of the 3-D Display System from 0175_8 to 0221_8 is not used by the Depth Testing Program. The flow diagram Figure A.10.d is replaced by the flow diagram shown in Figure D.3 for the Depth Testing Program. This is a key portion of the interconnection between the Depth Testing Program and the 3-D Display System. This interconnection section allows control of head movement or no head movement by bit Ø of the switch register. Bit Ø up ignores head motion. This section also provides an exit from the 3-D Display System to the Depth Testing Program when one of the buttons is pushed.

The sequence of commands at 1713_8 used to turn on the display and the turn off sequence at 3534_8 are different than the ones used in the 3-D Display System. The new on and off sequences more closely duplicate the sequence of events in the free running display and as a result, negligible on-off transients are produced.

The flow diagrams for the Depth Testing Program additions to the 3-D Display System are found in Figure D.4 for the setup section, Figure D.5 for the check section, and Figure

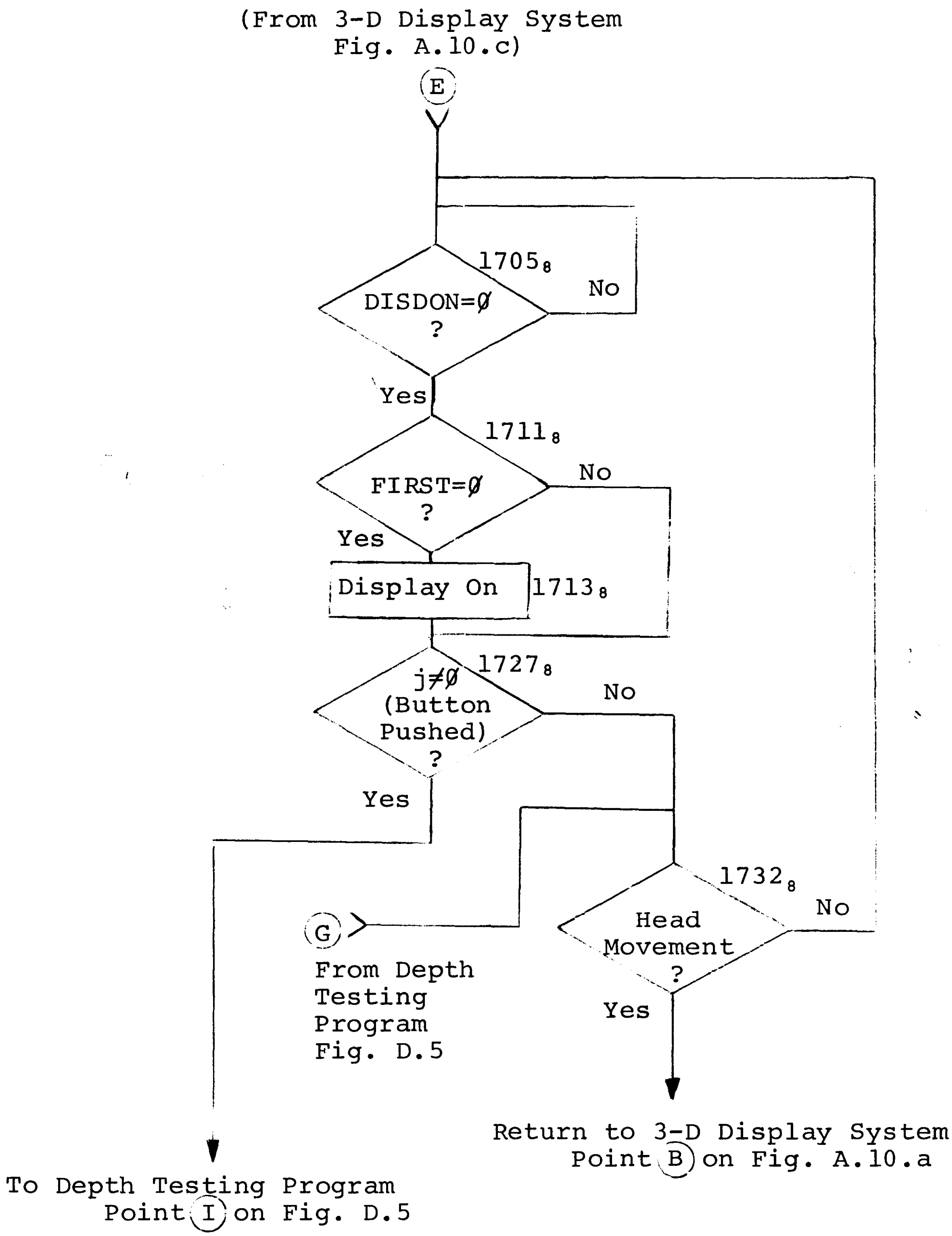


FIGURE D.3 REVISION TO FIG. A.10.d FOR DEPTH TESTING PROGRAM--3-D DISPLAY SYSTEM INTERCONNECTION

D.6 for the sequencing section. Octal numbers beside blocks indicate the corresponding location in PDP-8 core memory.

The initialization routine at 3413_8 in the setup section, Figure D.4, puts the analog display equipment in a ready state that is the same as if it had just been turned off. It then sets OMINUP←1 to prevent inertial updating by the 3-D Display System, MODE←1, TRIALS←WARMUP, initializes the variable pointer PNEXT to the start of the presentation sequence table TAB1 at 4040_8, and waits for the sense lines to be zero (j=Ø) before beginning the familiarization presentations.

The setup section changes the variable inertial list of the 3-D Display System so that the cube is at the specified depth for the trial. This routine starts at LOADGO, 3437_8. The depth identification number, i, is obtained from the presentation sequence table via the variable pointer PNEXT and stored in WHICH. CPDEPT is a constant pointer to the location before the start of the depth table TAB2 at 4020_8. CPDEPT + WHICH yields a pointer to the correct depth entry in TAB2. The depth is then added to the high order word of the triple precision X coordinate of each point of the cube and stored in the correct place in the variable inertial list. The other locations in the variable inertial list were initialized using preprogrammed coordinated maneuvers with the 3-D Display System by itself, then reversing the transfer direction in its initialization routine at 200_8 and storing the two

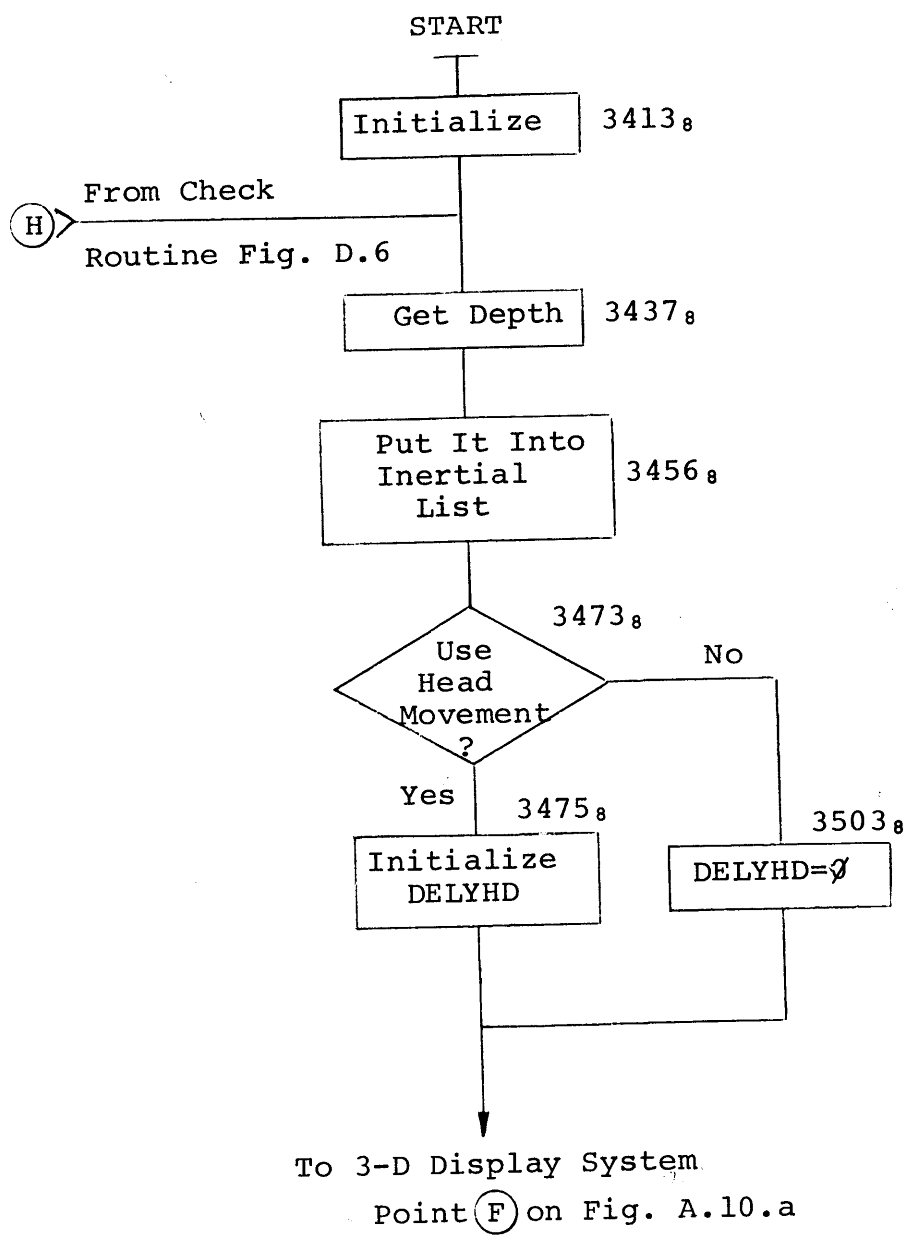


FIGURE D.4 FLOW DIAGRAM FOR DEPTH TESTING PROGRAM--SETUP SECTION

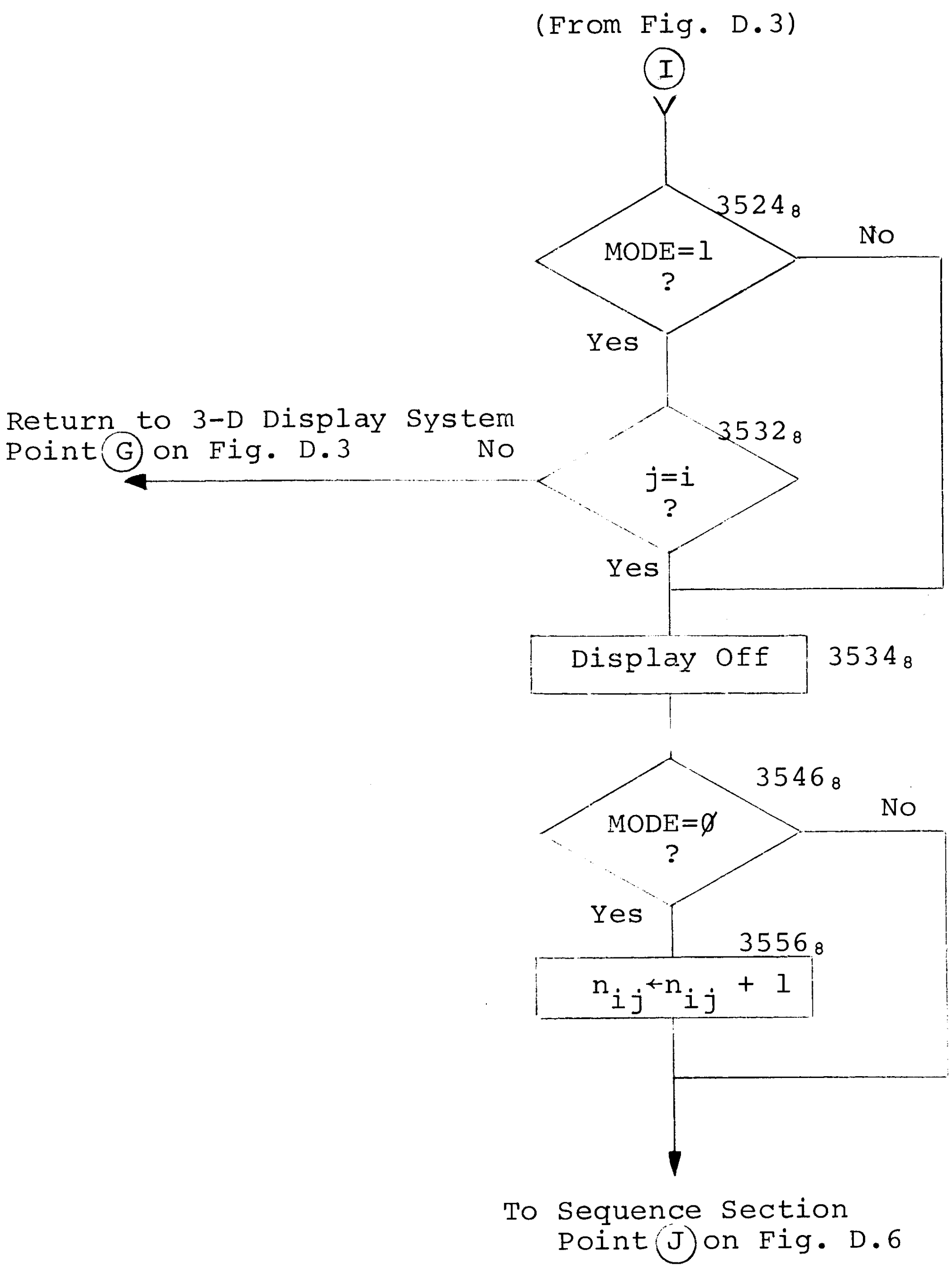


FIGURE D.5 FLOW DIAGRAM FOR DEPTH TESTING PROGRAM--CHECK SECTION

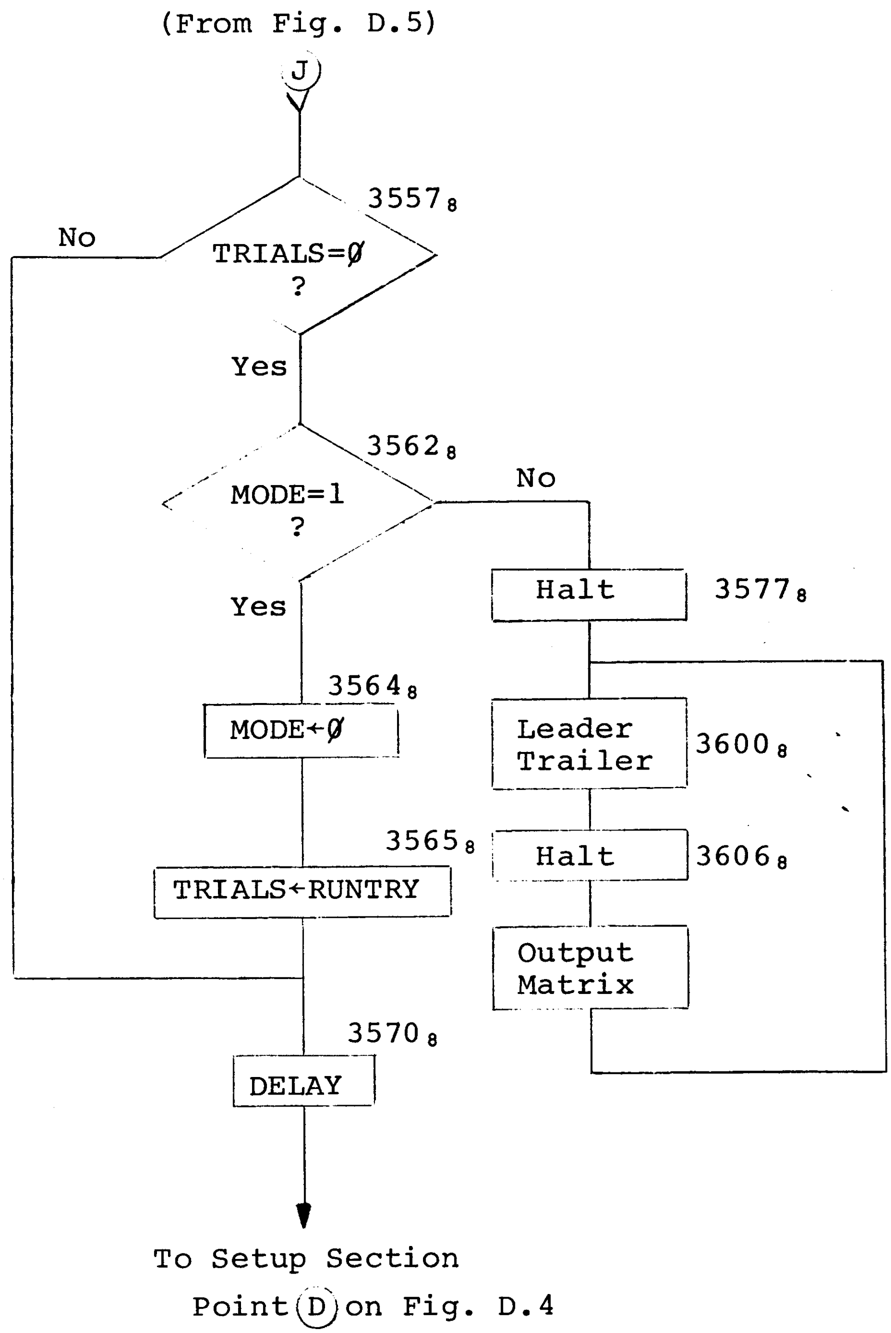


FIGURE D.6 FLOW DIAGRAM FOR DEPTH TESTING PROGRAM--SEQUENCING SECTION inertial lists on DECtape. The octal contents of the resulting inertial list are shown in Table D.1.

The initialization of the head position in the setup section was intended to eliminate transients by making the first frame correct for the subject's current head position. But it is ineffective because the amplifiers on the analog board used by the M.I.T. Instrumentation Laboratory Head Position Monitor (see Appendix B) are required by the display equipment to be in Pot Set Mode when the display is off. As a result the display always starts with head position assumed to be zero and goes to the correct head position with a time constant of 0.1 seconds caused by the lags used to remove amplifier noise.

The check section, Figure D.5, is entered from the 3-D Display System when a button is pressed by the subject to cause $j \neq 0$. The button number, j, in binary form is read from the sense lines. Control is returned to the 3-D Display System if $j \neq i$ during familiarization.

The program stores n_{ij} in matrix form by rows in the table DATA at 5000_8. The button number on the sense lines is j and WHICH is i. PDATA is a constant pointer to the location before table TAB3 at 4000_8. TAB3 contains constant pointers to the start of each row in the stimulus-response matrix. The pointer obtained from TAB3 via the pointer (PDATA + i) is added to j. The result is a pointer to the element of the S-R matrix which is to be incremented.

Octal Core Location	Octal Contents
3200	0773 1710 0420
3203	1032 2777 4610
3206	0777 7600 4200
3211	1000 7107 6230
3214	1005 5000 1720
3217	1044 6067 6450
3222	1037 0670 0340
3225	1040 0177 2730
3230	7762 7324 0200
3233	7756 2123 3620
3236	0022 4462 5420
3241	7762 0513 4540
3244	0021 5652 1740
3247	0015 0451 5220
3252	0015 7262 0760
3255	7755 3313 0000
3260	7763 0737 7460
3263	7755 3136 4100
3266	7763 0737 7460
3271	0022 4641 5210
3274	0022 4641 5210
3277	0014 7040 1630
3302	7755 3136 4100
3305	0014 7040 1630

TABLE D.1 THE PERMANENT INERTIAL LIST FOR THE ROTATED CUBE

The WAIT subroutine located at 3400_8 checks the sense lines for zero. If the sense lines are non-zero before 40 ms have elapsed the return is to the address of the calling instruction +1. If the sense lines are zero for the full 40 ms period the return is to the address of the calling instruction +2. The DELAY routine makes use of the WAIT subroutine to produce the waiting period between presentations. TIME is minus the number of times the WAIT subroutine must be successfully executed. Thus, the intertrial interval is a multiple of 40 ms. As presently set TIME = $-62_8 = 50_{10}$ which gives the 2 second delay.

The experiment is separated into two parts in the sequencing section, Figure D.6. MODE specifies the part. The parts are the familiarization trials (WARMUP specifies the number of them) and the experimental trials (RUNTRY specifies the number of them). TRIALS is counted down to zero to determine the end of a part.

The depth tables TAB2 that were used for the experiments are presented in Table D.2. The presentation sequence TAB1 that was used for all experiments is given in Table D.3. The table of the octal core locations corresponding to symbolic names appears on page 170. The pass three listing of the Depth Testing Program in PAL-III assembly language appears on pages 171 to 174.

```
                    /DEPTHS FROM 53.0--301.78 CM

                    *4020

4020    7530    0523-0773   /53.0
4021    7641    0634-0773   /64.3
4022    7771    0764-0773   /78.01
4023    0143    1136-0773   /94.64
4024    0344    1337-0773   /114.82
4025    0601    1574-0773   /139.30
4026    1077    2072-0773   /169.00
4027    1445    2440-0773   /205.03
4030    2075    3070-0773   /248.75
4031    2620    3613-0773   /301.78

                    /DEPTHS FROM 50.0--100.0 CM

                    *4020

4020    7506    0501-0773   /50.15
4021    7537    0532-0773   /54.00
4022    7572    0565-0773   /58.32
4023    7630    0623-0773   /62.99
4024    7670    0663-0773   /68.02
4025    7733    0726-0773   /73.47
4026    0001    0774-0773   /79.34
4027    0052    1045-0773   /85.69
4030    0125    1120-0773   /92.55
4031    0204    1177-0773   /99.95

                    /DEPTHS FROM 150--300 CM

                    *4020

4020    0705    1700-0773   /150.00
4021    1022    2015-0773   /162.00
4022    1145    2140-0773   /174.96
4023    1276    2271-0773   /188.96
4024    1437    2432-0773   /204.07
4025    1610    2603-0773   /220.40
4026    1770    2763-0773   /238.03
4027    2162    3155-0773   /257.07
4030    2366    3361-0773   /277.64
4031    2604    3577-0773   /299.85
```

TABLE D.2 THE DEPTH TABLES THAT WERE USED

```
/TABLE OF 22 FAMILIARIZATION SEQUENCE NUMBERS
/FOLLOWED BY 100 UNIFORMLY DISTRIBUTED
/UNCORRELATED RANDOM NUMBERS 1--10

*4040

DECIMAL
```

4040	0001	1
4041	0012	10
4042	0001	1
4043	0002	2
4044	0003	3
4045	0004	4
4046	0005	5
4047	0006	6
4050	0007	7
4051	0010	8
4052	0011	9
4053	0012	10
4054	0012	10
4055	0011	9
4056	0010	8
4057	0007	7
4060	0006	6
4061	0005	5
4062	0004	4
4063	0003	3
4064	0002	2
4065	0001	1
4066	0004	4
4067	0010	8
4070	0005	5
4071	0002	2
4072	0011	9
4073	0011	9
4074	0006	6
4075	0003	3
4076	0005	5
4077	0007	7
4100	0002	2
4101	0002	2
4102	0004	4
4103	0006	6
4104	0011	9
4105	0007	7
4106	0004	4
4107	0004	4
4110	0003	3
4111	0010	8
4112	0012	10
4113	0005	5
4114	0006	6
4115	0010	8
4116	0002	2
4117	0006	6
4120	0007	7
4121	0001	1
4122	0003	3
4123	0011	9
4124	0001	1
4125	0007	7
4126	0005	5
4127	0012	10
4130	0003	3
4131	0006	6
4132	0001	1
4133	0001	1
4134	0011	9
4135	0004	4
4136	0002	2
4137	0007	7
4140	0010	8
4141	0003	3
4142	0001	1
4143	0010	8
4144	0007	7
4145	0006	6
4146	0002	2
4147	0005	5
4150	0011	9
4151	0005	5
4152	0001	1
4153	0004	4
4154	0012	10
4155	0007	7
4156	0003	3
4157	0002	2
4160	0010	8
4161	0011	9
4162	0012	10
4163	0006	6
4164	0012	10
4165	0001	1
4166	0005	5
4167	0005	5
4170	0004	4
4171	0007	7
4172	0007	7
4173	0012	10
4174	0004	4
4175	0001	1
4176	0006	6
4177	0004	4
4200	0011	9
4201	0003	3
4202	0003	3
4203	0012	10
4204	0010	8
4205	0010	8
4206	0004	4
4207	0005	5
4210	0003	3
4211	0007	7
4212	0011	9
4213	0010	8
4214	0006	6
4215	0006	6
4216	0005	5
4217	0010	8
4220	0001	1
4221	0012	10
4222	0012	10
4223	0011	9
4224	0002	2
4225	0001	1
4226	0002	2
4227	0012	10
4230	0002	2
4231	0003	3

TABLE D.3 THE DEPTH PRESENTATION ORDER THAT WAS USED

A	3736
BCD	3703
BCD1	3732
BCD2	3733
BCD3	3734
BCD4	3735
BIN	3742
BINBCD	3661
CHECK	3523
CNTR	0041
CN12	3657
COR	3705
COUNT	0042
COVRT	3675
CPDEPT	3517
CPNEXT	3507
CT1	3741
C2	3743
C260	3650
C3	0062
C7	3506
C7700	3652
DATA	5000
DELAY	3570
DELYHD	0037
DISDON	0043
FIRST	0047
FRAME	0045
HOLD	1703
HOLDS	3412
HOLD1	0023
INIT1	3730
INIT2	3731
LF	3655
LOAD	3456
LOADGO	3437
LT	3660
MODE	3511
NEXT	3710
NFRAME	0065
NOTH	3635
NUM	3727
NVERT	0071
NXLINE	3613
OMINUP	0056
OUTPUT	3577
PCHECK	1735
PDATA	3522
PDEPTH	0022
PICOFF	3534
PNEXT	3510
PNR	3647
POINT	3653
PPRMIN	0111
PROGRS	3557
PTHREE	0114
PXIN	0117
PZERO	3512
P1	0020
P2	0021
RET	3654
RETURN	3520
RUNTRY	3521
SDATA	3651
SPCE	3656
START	3413
TAB1	4040
TAB2	4020
TAB3	4000
TEMP	3744
TIME	3514
TRIAD	0046
TRIALS	3516
TYPE	3640
WAIT	3400
WARMUP	3515
WHICH	0132
ZEROS	3513

```
                DELYHD=37
                COUNT=42
                C3=62
                P1=20
                P2=21
                PDEPTH=22
                HOLD1=23
                PXIN=117
                PPRMIN=111
                NVERT=71
                WHICH=132
                OMINUP=56
                DISDON=43
                FRAME=45
                TRIAD=46
                FIRST=47
                NFRAME=65
                PTHREE=114
                CNTR=41


                *1703
1703    6301    HOLD,CCL01
1704    1043    TAD Z DISDON
1705    7640    SZA CLA
1706    5304    JMP .-2
1707    6302    SCL01
1710    1047    TAD Z FIRST
1711    7640    SZA CLA
1712    5326    JMP .+14
1713    6002    IOF
1714    6351    SCL08
1715    1065    TAD Z NFRAME
1716    3045    DCA Z FRAME
1717    7240    CLA CMA
1720    3046    DCA Z TRIAD
1721    7001    IAC
1722    3047    DCA FIRST
1723    6452    CMR
1724    6402    AMC
1725    6001    ION
1726    6435    CAC SLR
1727    7640    SZA CLA
1730    5735    JMP I PCHECK
1731    7604    LAS
1732    7710    SPA CLA
1733    5303    JMP HOLD
1734    5514    JMP I PTHREE
1735    3523    PCHECK,CHECK
```

```
                *3400
3400    0000    WAIT,0
3401    3212    DCA HOLDS
3402    6316    SCL03 CCL03
3403    6435    CAC SLR
3404    7640    SZA CLA
3405    5600    JMP I WAIT
3406    2212    ISZ HOLDS
3407    5203    JMP .-4
3410    2200    ISZ WAIT
3411    5600    JMP I WAIT
3412    0000    HOLDS,0

3413    6342    START,SCL07
3414    6344    CCL08
3415    6454    CLIF
3416    7001    IAC
3417    3056    DCA OMINUP
3420    7001    IAC
3421    3311    DCA MODE
3422    1312    TAD PZERO
3423    3010    DCA Z 10
3424    1313    TAD ZEROS
3425    3042    DCA COUNT
3426    3410    DCA I Z 10
3427    2042    ISZ COUNT
3430    5226    JMP .-2
3431    1307    TAD CPNEXT
3432    3310    DCA PNEXT
3433    1315    TAD WARMUP
3434    3316    DCA TRIALS
3435    4200    JMS WAIT
3436    5235    JMP .-1

3437    1710    LOADGO,TAD I PNEXT
3440    2310    ISZ PNEXT
3441    3132    DCA WHICH
3442    1132    TAD WHICH
3443    1317    TAD CPDEPT
3444    3022    DCA PDEPTH
3445    1071    TAD NVERT
3446    7041    CIA
3447    3042    DCA COUNT
3450    1111    TAD PPRMIN
3451    7001    IAC
3452    3020    DCA P1
3453    1117    TAD PXIN
3454    7001    IAC
```

```
3455  3021  DCA P2
3456  1420  LOAD,TAD I P1
3457  1422  TAD I PDEPTH
3460  3421  DCA I P2
3461  1020  TAD P1
3462  1062  TAD C3
3463  3020  DCA P1
3464  1021  TAD P2
3465  1062  TAD C3
3466  3021  DCA P2
3467  2042  ISZ COUNT
3470  5256  JMP LOAD
3471  7604  LAS
3472  7004  RAL
3473  7710  SPA CLA
3474  5303  JMP .+7
3475  1306  TAD C7
3476  6543  ADCC ADSC
3477  6532  ADCV
3500  6531  ADSF
3501  5300  JMP .-1
3502  6534  ADRB
3503  3037  DCA DELYHD
3504  5705  JMP I .+1
3505  0222  0222
3506  0007  C7,7
3507  4040  CPNEXT,TAB1
3510  0000  PNEXT,0
3511  0000  MODE,0
3512  4777  PZERO,DATA-1
3513  7634  ZEROS,-144
3514  7716  TIME,-62
3515  7752  WARMUP,-26
3516  0000  TRIALS,0
3517  4017  CPDEPT,TAB2-1
3520  1731  RETURN,1731
3521  7634  RUNTRY,-144
3522  3777  PDATA,TAB3-1

3523  1311  CHECK,TAD MODE
3524  7650  SNA CLA
3525  5334  JMP PICOFF
3526  6435  CAC SLR
3527  6316  SCL03 CCL03
3530  7041  CIA
3531  1132  TAD WHICH
3532  7640  SZA CLA
3533  5720  JMP I RETURN
3534  6452  PICOFF,CMR
3535  6404  AMPS
3536  6002  IOF
3537  6461  SKIF
3540  7410  SKP
3541  5337  JMP .-2
3542  6454  CLIF
3543  6342  SCL07
3544  6344  CCL08
3545  1311  TAD MODE
3546  7640  SZA CLA
3547  5357  JMP PROGRS
3550  1132  TAD WHICH
3551  1322  TAD PDATA
3552  3132  DCA WHICH
3553  6435  CAC SLR
3554  1532  TAD I WHICH
3555  3132  DCA WHICH
3556  2532  ISZ I WHICH
3557  2316  PROGRS,ISZ TRIALS
3560  5370  JMP DELAY
3561  1311  TAD MODE
3562  7650  SNA CLA
3563  5377  JMP OUTPUT
3564  3311  DCA MODE
3565  1321  TAD RUNTRY
3566  3316  DCA TRIALS
3567  7402  HLT

3570  1314  DELAY,TAD TIME
3571  3023  DCA HOLD1
3572  4200  JMS WAIT
3573  5370  JMP .-3
3574  2023  ISZ HOLD1
3575  5372  JMP .-3
3576  5237  JMP LOADGO
```

```
3577  7402  OUTPUT,HLT
3600  1252  TAD C7700
3601  3042  DCA COUNT
3602  1260  TAD LT
3603  4240  JMS TYPE
3604  2042  ISZ COUNT
3605  5202  JMP .-3
3606  7402  HLT
3607  1257  TAD CN12
3610  3042  DCA COUNT
3611  1251  TAD SDATA
3612  3247  DCA PNR
3613  1257  NXLINE,TAD CN12
3614  3041  DCA CNTR
3615  1647  TAD I PNR
3616  2247  ISZ PNR
3617  4261  JMS BINBCD
3620  1334  TAD BCD3
3621  4240  JMS TYPE
3622  1335  TAD BCD4
3623  4240  JMS TYPE
3624  2041  ISZ CNTR
3625  5235  JMP NOTH
3626  1254  TAD RET
3627  4240  JMS TYPE
3630  1255  TAD LF
3631  4240  JMS TYPE
3632  2042  ISZ COUNT
3633  5213  JMP NXLINE
3634  5200  JMP OUTPUT+1
3635  1256  NOTH,TAD SPCE
3636  4240  JMS TYPE
3637  5215  JMP NXLINE+2

3640  0000  TYPE,0
3641  1250  TAD C260
3642  6046  TLS
3643  6041  TSF
3644  5243  JMP .-1
3645  7300  CLA CLL
3646  5640  JMP I TYPE

3647  0000  PNR,0
3650  0260  C260,260
3651  5000  SDATA,DATA
3652  7700  C7700,7700
3653  7776  POINT,256-260
3654  7735  RET,215-260
3655  7732  LF,212-260
3656  7760  SPCE,240-260
3657  7766  CN12,-12
```

```
3660  7720  LT,200-260
3661  0000  BINBCD,0
3662  3342  DCA BIN
3663  3332  DCA BCD1
3664  3333  DCA BCD2
3665  3334  DCA BCD3
3666  3335  DCA BCD4
3667  1327  TAD NUM
3670  3341  DCA CT1
3671  1330  TAD INIT1
3672  3275  DCA COVRT
3673  1331  TAD INIT2
3674  3303  DCA BCD
3675  1336  COVRT,TAD A
3676  1342  TAD BIN
3677  7510  SPA
3700  5310  JMP NEXT
3701  3342  DCA BIN
3702  7100  CLL
3703  2332  BCD,ISZ BCD1
3704  5275  JMP COVRT
3705  7100  COR,CLL
3706  1344  TAD TEMP
3707  5301  JMP .-6
3710  3344  NEXT,DCA TEMP
3711  1341  TAD CT1
3712  0343  AND C2
3713  7440  SZA
3714  5317  JMP .+3
3715  7430  SZL
3716  5305  JMP COR
3717  7300  CLA CLL
3720  2275  ISZ COVRT
3721  2303  ISZ BCD
3722  2341  ISZ CT1
3723  5275  JMP COVRT
3724  1342  TAD BIN
3725  3335  DCA BCD4
3726  5661  JMP I BINBCD
3727  7775  NUM,7775
3730  1336  INIT1,TAD A
3731  2332  INIT2,ISZ BCD1
3732  0000  BCD1,0
3733  0000  BCD2,0
3734  0000  BCD3,0
3735  0000  BCD4,0
3736  6030  A,6030
3737  7634  7634
3740  7766  7766
3741  0000  CT1,0
3742  0000  BIN,0
3743  0002  C2,2
3744  0000  TEMP,0
```

```
            *4000

            /POINTERS TO START OF ROW OF MATRIX -1

4000  4777  TAB3,DATA-1
4001  5011  DATA+11
4002  5023  DATA+23
4003  5035  DATA+35
4004  5047  DATA+47
4005  5061  DATA+61
4006  5073  DATA+73
4007  5105  DATA+105
4010  5117  DATA+117
4011  5131  DATA+131


            *4020

4020  0000  TAB2,0          /TABLE OF DEPTHS


            *4040

4040  0000  TAB1,0          /TABLE OF PRESENTATION ORDER


            *5000
            /MATRIX OF EXPERIMENTAL RESULTS
            /STORED BY ROWS
            /EACH ROW IS STIMULUS
            /EACH COLUMN IS RESPONSE

5000  0000  DATA,0
```

APPENDIX E

ANALYTICAL TECHNIQUES

The data resulting from the depth perception experiments was a stimulus-response matrix $[n_{ij}]$ where the element n_{ij} is the number of times the j-th push button, PB_j, was selected in response to the i-th stimulus depth, D_i. In essence $[n_{ij}]$ is an estimate of the bivariate joint discrete probability distribution between D and PB

$$\hat{P}(D_i, PB_j) = \frac{n_{ij}}{N}$$

where

$$N = \sum_{i=1}^{I} \sum_{j=1}^{J} n_{ij}$$

I is the number of values that D_i takes and J is the number of push buttons available to the subject. In the experiment, the subject was given the opportunity to make just as many different responses as there were stimuli,

$$I = J$$

The notation for the upper bound will be omitted unless it is neither I nor J. The lower bound will always be 1.

The stimulus-response matrices were analyzed to determine the information transmission from the depth displayed to the subject's button selection, $T(D_i, PB_j)$. Information transmission[1] is a measure of the effectiveness of a response in changing the prior probability that the stimulus D_i was presented, $P(D_i)$. That is, it is a measure of how much sharper the peak is in the posterior probability distribution of the stimulus D_i given the response PB_j, $P(D_i|PB_j)$, than in the prior distribution $P(D_i)$. Thus the information transmitted by the button selection about the depth measures how well the actual depth is known from what the subject says it is.

The information transmitted by PB_j about D_i is defined as a function only of the prior and posterior probabilities of D_i given PB_j

$$T(D_i, PB_j) = G\{F[P(D_i), P(D_i|PB_j)]\}$$

The functional form $F\{P(D_i), P(D_i|PB_j)\}$ is completely determined by requiring that the information transmitted from two independent stimuli considered as a single event, (D_i, D_k), to two responses considered as a single event, (PB_j, PB_ℓ), be the sum of the information transmitted by each response. That is, the information transmitted by two stimulus-response pairs must be the same whether the transmission is considered to be a parallel or serial process.

With the preceding restrictions, the form of the information given by a single response to a single stimulus may be derived. See Attneave for the steps in the derivation. The resulting form is

$$F(D_i,PB_j) \equiv F\{P(D_i),P(D_i|PB_j)\} = -A \log \frac{P(D_i|PB_j)}{P(D_i)}$$

Since the choice of the arbitrary constant A is equivalent to the choice of the arbitrary base for the logarithm, A will be chosen to be -1. The choice of the base for the logarithm determines the size of a unit of information. Note that if

$$P(D_i|PB_j) = P(D_i)$$

then

$$F(D_i,PB_j) = \log 1 = 0$$

That is, the information given by the response is zero if no more is known after a response about which stimulus occurred. If

$$P(D_i|PB_j) = 1$$

then

$$F(D_i,PB_j) = \log \frac{1}{P(D_i)}$$

that is, if the stimulus is perfectly identified by the response the information given by the response is the logarithm of the inverse probability of the stimulus. For a uniformly distributed stimulus

$$P(D_i) = \frac{1}{I}$$

and

$$F(D_i,PB_j) = \log I$$

for the case of perfect identification. This suggests that

I is one convenient base for the logarithm. Perfect information is unity when the base I is used. The base 2 was used for the logarithm in this thesis because the powers of 2 are in general more familiar than other bases except 10. Use of the base 2 expresses F in binary bits and an increase of unity in F represents a doubling of information.

The information transmitted from D_i to PB_j by many stimulus-response pairs is defined as the sum of the F's for each pair weighted by the probability of occurrence for that pair

$$T(D_i,PB_j) = G\{F\} = \sum_i \sum_j P(D_i,PB_j) \log \frac{P(D_i|PB_j)}{P(D_i)}$$

This expression for T retains the properties of F.

Using the S-R matrix $[n_{ij}]$ to estimate the joint probability distribution $P(D_i,PB_j)$ as

$$\hat{P}(D_i,PB_j) = \frac{n_{ij}}{N}$$

the probability $P(D_i)$ as

$$\hat{P}(D_i) = \frac{1}{N} \sum_j n_{ij} \equiv \frac{n_i}{N}$$

(where n_i is the number of times the i-th depth was presented) and the conditional probability $P(D_i|PB_j)$ as

$$P(D_i|PB_j) = \frac{n_{ij}}{\sum_i n_{ij}} \equiv \frac{n_{ij}}{n_j}$$

(where n_j is the number of times the j-th button was selected) an estimate of the information transmitted from all D_i to all PB_j is obtained

$$\hat{T}(D_i, PB_j) = \sum_i \sum_j \frac{n_{ij}}{N} \log \frac{n_{ij}/n_j}{n_i/N}$$

Consider an experiment in which eight depths are each presented ten times and the subject is provided with eight push buttons. That is

$$I = 8$$

$$n_i = 10$$

$$N = n_i I = 80$$

$$J = 8$$

For the special case of a uniformly distributed stimulus

$$P(D_i) = \frac{1}{I}$$

the estimate of information transmission becomes

$$\hat{T}(D_i, PB_j) = \sum_i \sum_j \frac{n_{ij}}{N} \log I\left(\frac{n_{ij}}{n_j}\right)$$

Thus for this example

$$\hat{T}(D_i, PB_j) = \sum_i \sum_j \frac{n_{ij}}{80} \log 8\left(\frac{n_{ij}}{n_j}\right)$$

Suppose the subject selects button 1 every time depths 1 through 4 are presented and button 8 every time depths 5 through 8 are presented that is

$$n_{11} = n_{21} = n_{31} = n_{41} = n_{58} = n_{68} = n_{78} = n_{88} = 10$$

with all other $n_{ij} = 0$. Then

$$\hat{T}(D_i, PB_j) = 8\{\frac{10}{80} \log_2 8(\frac{10}{40})\} = \log_2 2 = 1$$

Suppose another subject selects button 1 every time depths 1 and 2 are presented, button 3 every time depths 3 and 4 are presented, etc. That is

$$n_{11} = n_{21} = n_{33} = n_{43} = n_{55} = n_{65} = n_{77} = n_{87} = 10$$

with all other $n_{ij} = 0$. Then

$$\hat{T}(D_i, PB_j) = 8\{\frac{10}{80} \log_2 8(\frac{10}{20})\} = \log_2 4 = 2$$

Thus it is seen that the subject is discriminating the depth range, D_1 to D_I, into $2^{\hat{T}}$ intervals. This property of the measured information transmission is very useful in analyzing changes in depth perception resulting from changes in the depth cues incorporated in a display.

Since the information transmission is expressed as a logarithm, an increase $\Delta\hat{T}$ in $\hat{T}$ is an addition of logs which is equivalent to multiplying the original discrimination by a factor $2^{\Delta\hat{T}}$. Thus the percentage increase in discrimination is given by

$$\% \text{ improvement} = \frac{2^{\Delta\hat{T}} - 1}{100}$$

in terms of the change in the estimated information transmission.

In order to determine the statistical significance of the difference in the S-R matrices, bivarate correlation analysis[5] is used. The estimation of the joint probability of the S-R pair may be modeled by a bivarate normal distribution. Then the estimate of the correlation coefficient

$$\hat{P} = \frac{N\{\sum_i \sum_j i\ j\ n_{ij}\} - \{\sum_i i\ n_{i\cdot}\}\{\sum_j j\ n_{\cdot j}\}}{\sqrt{N \sum_i i^2\ n_{i\cdot} - \{\sum_i i\ n_{i\cdot}\}^2}\ \sqrt{N \sum_j j^2\ n_{\cdot j} - \{\sum_j j\ n_{\cdot j}\}^2}}$$

measures spread of the S-R pairs around the principle diagonal. The quantity

$$z = \frac{\sqrt{N-3}}{2} \log_e \frac{(1 + \hat{\rho})\ (1 - \rho)}{(1 - \hat{\rho})\ (1 + \rho)}$$

has approximately the standard normal distribution. A table of areas under the standard normal distribution may be used to determine the confidence level, α, that the estimated correlation coefficient $\hat{\rho}$ did not come from the parent distribution with correlation coefficient ρ. The range in ρ such that $\hat{\rho}$ would have a confidence level greater than or equal to $(1 - \alpha)$ of having come from the parent distribution with correlation ρ may be derived using z and the inequality

$$-z_{\alpha/2} \leq z \leq z_{\alpha/2}$$

The result is that

$$\frac{1+\hat{\rho}-(1-\hat{\rho})e^{2z_{\alpha/2}/\sqrt{N-3}}}{1+\hat{\rho}+(1-\hat{\rho})e^{2z_{\alpha/2}/\sqrt{N-3}}} \leq \rho \leq \frac{1+\hat{\rho}-(1-\hat{\rho})e^{-2z_{\alpha/2}/\sqrt{N-3}}}{1+\hat{\rho}+(1-\hat{\rho})e^{-2z_{\alpha/2}/\sqrt{N-3}}}$$

Then equating the upper limit of the confidence interval determined from $\hat{\rho}_1$ and the lower limit from $\hat{\rho}_2$

$$z_{\alpha/2} = \frac{\sqrt{N-3}}{4} \log_e \frac{(1 + \hat{\rho}_2)\ (1 - \hat{\rho}_1)}{(1 - \hat{\rho}_2)\ (1 + \hat{\rho}_1)}$$

where α is the confidence that $\hat{\rho}_1$ and $\hat{\rho}_2$ did not come from the same distribution. This is the way that the significance of the difference in the S-R matrices was determined.

The calculation of the estimated information transmission from the S-R matrix was implemented on the PDP-8 computer using the Fortran program listed on pages 189 to 190. The formula for estimated information transmission

$$\hat{T}(D_i, PB_j) = \sum_i \sum_j \frac{n_{ij}}{N} \log \frac{n_{ij}/n_j}{n_i/N}$$

is expressed in the form

$$\hat{T}(D_i, PB_j) = \log N - \frac{1}{N}\{\sum_i n_i \log n_i + \sum_j n_j \log n_j - \sum_i \sum_j n_{ij} \log n_{ij}\}$$

The same program also computes the estimate of correlation coefficient from

$$\hat{\rho} = \frac{N\{\sum_i \sum_j i\ j\ n_{ij}\} - \{\sum_i i\ n_i\}\ \{\sum_j j\ n_j\}}{\sqrt{N \sum_i i^2\ n_i - \{\sum_i i\ n_i\}^2}\ \sqrt{N \sum_j j^2\ n_j - \{\sum_j j\ n_j\}^2}}$$

The program also computes two measures which were not used in the presentation of this thesis. One is the set of means and standard deviations on each row $\hat{m}_i$, $\hat{\sigma}_i$ and the whole matrix along the major diagonal $\hat{m}$, $\hat{\sigma}$ according to

$$\hat{m}_i = \frac{1}{n_i} \sum_j (j-i)\ n_{ij}$$

$$\hat{\sigma}_i = \sqrt{\frac{1}{n_i} \sum_j \{(j-i)\ n_{ij}\}^2 - \hat{m}_i^{\,2}}$$

$$\hat{m} = \frac{1}{N} \sum_i \sum_j (j-i)\ n_{ij}$$

$$\hat{\sigma} = \sqrt{\frac{1}{N} \sum_i \sum_j \{(j-i)\ n_{ij}\}^2 - m^2}$$

The other, T_A, penalizes stimulus-response pairs off the principle diagonal. It is given by

$$T_A = 1 - \frac{I \sum_i \sum_j |j-i|\ n_{ij}}{N(A + \sum_{i=1}^{B} i)}$$

where

$$\left.\begin{aligned} A &= \frac{I^2}{2} \\ B &= \frac{I}{2} \end{aligned}\right\} \text{ if } I \text{ is even}$$

$$\left.\begin{aligned} A &= \frac{I(I-1)}{2} \\ B &= \frac{I-1}{2} \end{aligned}\right\} \text{ if } I \text{ is odd}$$

The means and standard deviations of the intensification amplitude versus line length data from the experiments were calculated using

$$\hat{m}_i = \frac{1}{N_i} \sum_{n=1}^{N_i} A_{n,i}$$

and

$$\hat{\sigma}_i = \sqrt{\frac{1}{N_i} \sum_{n=1}^{N_i} A_{n,i}^2 - \hat{m}_i^{\,2}}$$

where the subscript i refers to the i-th line length, $\hat{m}_i$ is the estimate of the mean, $\hat{\sigma}_i$ is the estimate of the standard deviation, $A_{n,i}$ is each intensification amplitude selected by the subject, and N_i is number of data points at the i-th length.

The data was punched on paper tape by the Intensity Testing Program (see Appendix C). The data on paper tape served as input to the PDP-8 Fortran program listed on page 191, which was used to compute $\hat{m}_i$ and $\hat{\sigma}_i$ for each subject and the composite of subjects. Parameters to be entered via teletype before the input of data are (1) number of subjects, (2) number of data points per line length per subject, and (3) number of line lengths.

The DO loop on 5 is used to ignore the statistics outputted by the Intensity Testing Program. The output format for one line of print is $\hat{m}_i$, $\hat{\sigma}_i$ for the current subject and $\hat{m}_i$, $\hat{\sigma}_i$ for the composite of the current subject and all previous subjects. The first printed line of a group corresponds to the first line length and they correspond in consecutive order.

A curve was fit to the means of the intensification amplitudes, $\hat{m}_i$. The mathematical form of the curve used is

$$A(L) = C_1 + C_2 L^{C_3}$$

where A(L) is the intensification as a function of the line length L and C_1, C_2, C_3 are constants to be determined so that

$$\Phi(C_1,C_2,C_3) = \sum_{i=1}^{I} \{C_1 + C_2 L_i^{C_3} - A(L_i)\}^2$$

is minimized subject to the constraint

$$\Psi(C_1,C_2,C_3) = \sum_{i=1}^{I} \{C_1 + C_2 L_i^{C_3} - A(L_i)\} = 0$$

where L_i is the i-th length in a set of I line lengths.

The constant C_1 may be guessed and C_2,C_3 found from a best fit on a log-log plot. That is

$$A(L) - C_1 = C_2 L^{C_3}$$

$$\log [A(L) - C_1] = \log C_2 + C_3 \log L$$

and C_2,C_3 are found by minimizing

$$\Phi|_{C_1} = \Phi(C_2,C_3) = \sum_{i=1}^{I} \{\log C_2 + C_3 \log L_i - \log [A(L_i)-C_1]\}^2$$

subject to the constraint

$$\Psi|_{C_1} = \Psi(C_2,C_3) = \sum_{i=1}^{I} \{\log C_2 + C_3 \log L_i - \log [A(L_i)-C_1]\} = 0$$

C_2 and C_3 are found analytically from

$$\log C_2 = \overline{y} - C_3 \overline{x}$$

and

$$C_3 = \frac{\overline{xy} - \overline{x}\,\overline{y}}{\overline{x^2} - x^2}$$

where

$$\overline{x} = \frac{1}{I}\sum_{i=1}^{I} \log L_i$$

$$\overline{x^2} = \frac{1}{I}\sum_{i=1}^{I} \{\log L_i\}^2$$

$$\overline{y} = \frac{1}{I}\sum_{i=1}^{I} \{\log [A(L_i)-C_1]\}$$

$$\overline{xy} = \frac{1}{I}\sum_{i=1}^{I} \{\{\log L_i\}\{\log [A(L_i)-C_1]\}\}$$

Now C_1 may be found by minimizing

$$\Phi(C_1) = \Phi\big|_{C_1}$$

The shape of $\Phi(C_1)$ is indicated qualitatively in Figure E.? $\Phi(C_1)$ tends to zero as C_1 becomes more negative. This corresponds to adding a larger constant to A(L). Then C_1 dominates and C_3 tends to zero as C_2 tends to infinity. On a log-log plot this would be a horizontal line, not a valid fit to the data. $\Phi(C_1)$ increases as C_1 becomes large. This corresponds to decreasing C_2 and increasing C_3 resulting in a lower line with greater slope on the log-log plot. C_1 is constrained to be less than the smallest $A(L_i)$ because logarithms of negative numbers are not defined.

A local maximum and minimum of $\Phi(C_1)$ are between the two extreme cases. The local minimum is the valid solution for C_1. See Figure 2.2 for a log-log plot of A(L) and $\{A(L)-C_1\}$ where C_1 is at the local minimum. But $\Phi(C_1)$ is

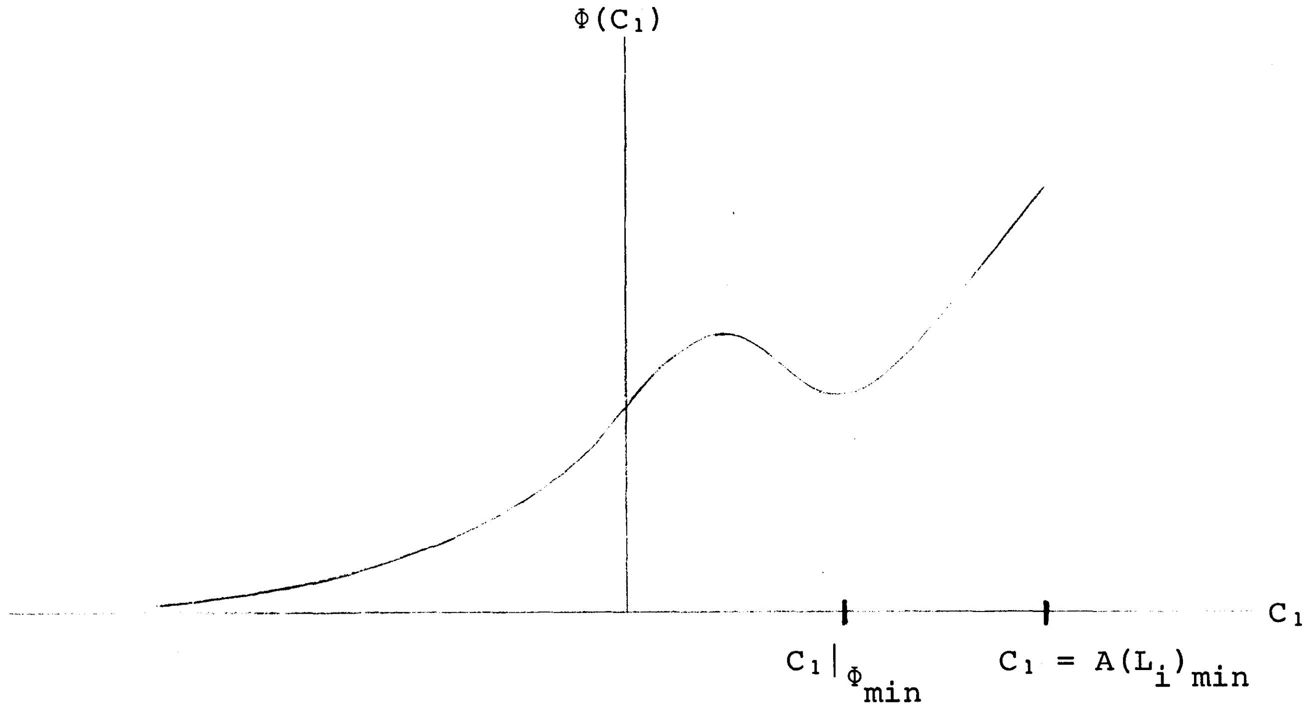


FIGURE E.1 SHAPE OF $\Phi(C_1)$ VERSUS C_1

monotonic if the chosen functional form, $A(L) = C_1 + C_2 L^{C_3}$, is not appropriate to be used to fit the set of data. The difference in $\Phi(C_1)$ between the local maximum and minimum is a measure of the appropriateness of functional form of A(L).

This procedure was implemented using the PDP-8 Fortran program listed on page 192. The set of line lengths, $L_i \equiv X_i$, are written into the program. The data is inputted via the teletype in consecutive order from $A_1 \equiv Y_1$. The parameters C_1, C_2, C_3 are named C, A, B respectively. The minimum of $\Phi(C_1)$ was found by a simple search with a constant step size moving in the direction of the minimum, starting from a value of C_1 inputted via the teletype. When the minimum for a given step size is reached, the step size is reduced and the procedure continued until a minimum step size is reached. The output format is C_1, C_2, C_3, $\Phi(C_1)$ for each step.

```
C; ANALYSIS OF STIMULUS-RESPONSE MATRIX

C; PARAMETERS  ARE  : NI, NJ, NK, NS
C; USED SWITCHES :
C;  SW 4 :  ON = ONE MATRIX
C;         OFF = ADD ANOTHER MATRIX
C;  SW 3 :  ON = TO GET LEADER-TRAILER
C;         OFF = NO LEADER-TRAILER
C;  SW 2 :  ON = ACCEPTS  NEW  NS
C;         OFF = WORKS WITH SAME NS
C;  SW 1 :  ON = COMES BACK TO THE TOP
C:         OFF = WORKS WITH SAME  NI,NJ,NK

C;DEFINITION OF SWITCHES

 ;DIMENSION ITCH(26)
 ;ITCH=4
 ;ISW4=ISW3=ISW2=ISW1

C;FORMATTING

101;FORMAT(/,"NI,NJ,NK",/)
102;FORMAT(/,"NS",/)
103;FORMAT(/,/,"MATRIX",I,/,/)
104;FORMAT("")
110;FORMAT(/)
111;FORMAT(I)
112;FORMAT(/,I,E,E)
113;FORMAT(/,E,E,/)

C;MATRIX READING

  ;I1=1
  ;I2=2
 ;DIMENSION IA(100)
1;TYPE 101
 ;ACCEPT 111,NI,NJ,NK
 ;NN=0
 ;ND=NI/I2
 ;DO 19 L=1,ND
 ;NN=NN+L
19;CONTINUE
 ;L=NI-I2*ND
 ;IF(L)1,17,18
17;NN=I2*NN+NI*ND
 ;GO TO 2
18;NN=I2*NN+(NI+I1)*NI/I2
2;TYPE 102
 ;ACCEPT 111,NS
42;DO 10 I=1,NI
 ;DO 10 J=1,NJ
 ;INDX=J+NJ*(I-I1)
 ;IA(INDX)=0
10;CONTINUE
 ;K=0
 ;GO TO 22
21;NS=NS+I1
 ;K=NS
22;FNI=NI
 ;NKS=NK*NS
 ;FNKS=NKS
 ;N=NI*NKS
 ;FN=N
20;TYPE 103,K
 ;DO 11 I=1,NI
 ;DO 11 J=1,NJ
 ;ACCEPT 111,IB
 ;INDX=J+NJ*(I-I1)
 ;IA(INDX)=IA(INDX)+IB
11;CONTINUE
 ;IF(K-NS)20,29,29
29;PAUSE

C;RESULTANT MATRIX

 ;PAUSE 3941
 ;GO TO (23,24),ISW3
23;DO 25 L=1,64
 ;TYPE 104
24;CONTINUE
 ;TYPE 110
 ;DO 27 I=1,NI
 ;DO 26 J=1,NJ
 ;INDX=J+NJ*(I-I1)
 ;TYPE 111,IA(INDX)
26;CONTINUE
 ;TYPE 110
27;CONTINUE
 ;PAUSE 3941
 ;GO TO (28,25),ISW3
28;DO 29 L=1,64
 ;TYPE 104
25;CONTINUE
 ;PAUSE
```

```
C;INITIALIZATION AND SUMMATION

 ;SI=SJ=SIJ=0.
 ;IS=0
 ;FM=FS=FMT=FST=0.
 ;CI=CI2=CJ=CJ2=CIJ=0.
 ;DO 12 I=1,NI
 ;FI=I
 ;SA=0.
 ;DO 34 J=1,NJ
 ;FJ=J
 ;INDX=J+NJ*(I-I1)
 ;ID=I-J
 ;IF(ID)15,16,16
15;ID=-ID
16;IS=IS+ID*IA(INDX)
 ;RIJ=IA(INDX)
 ;CIJ=CIJ+RIJ*FI*FJ
 ;X=FJ*RIJ
 ;FM=FM+X
 ;FS=FS+X*X
 ;IF(RIJ)1,31,30
30;SA=SA+RIJ
 ;SIJ=SIJ+RIJ*LOGF(RIJ)
31;CONTINUE
 ;XI=FI*FNKS
 ;CI=CI+XI
 ;CI2=CI2+FI*XI
 ;Y=FM-FI
 ;FMT=FMT+Y
 ;FMC=Y/FNKS
 ;X=FS-Y*Y
 ;FST=FST+FS
 ;FSC=SQTF(X)/FNKS
 ;IF(SI)1,34,32
32;SI=SI+SA*LOGF(SA)
34;TYPE 112,I,FMC,FSC
12;CONTINUE
 ;TYPE 110

C;MEAN - STANDARD DEVIATION

 ;FST=SQTF(FST-FMT*FMT)/FN
 ;FMT=FMT/FN
 ;TYPE 113,FMT,FST
```

```
C;INFORMATION TRANSMISSION

 ;DO 13 J=1,NJ
 ;SA=0.
 ;DO 14 I=1,NI
 ;INDX=J+NJ*(I-I1)
 ;RIJ=IA(INDX)
 ;SA=SA+RIJ
 ;YJ=FJ*FNKS
 ;CJ=CJ+YJ
 ;CJ2=CJ2+FJ*YJ
14;CONTINUE
 ;IF(SA)1,13,33
33;SJ=SJ+SA*LOGF(SA)
13;CONTINUE
 ;TC=(LOGF(FN)-(SI+SJ-SIJ)/FN)'
     /LOGF(FNI)
 ;TYPE 113,TC

C;BIVARIATE CORRELATION

 ;X=SQTF(FN*CI2-CI*CI)
 ;Y=SQTF(FN*CJ2-CJ*CJ)
 ;XI=FN*CIJ-CI*CJ
 ;YI=X*Y
 ;TB=XI/YI
 ;TYPE 113,TB

C;ACCURACY FACTOR

 ;FNN=NN
 ;FIS=IS
 ;TA=1.-FNI*FIS/(FN*FNN)
 ;TYPE 113,TA


 ;PAUSE 3941
 ; GO TO (1,40),ISW1
40;GO TO (2,41),ISW2
41;GO TO(42,21),ISW4

 ;END
```

```
C; PROGRAM TO COMPUTE MEAN AND STANDARD DEVIATION
C; OF INTENSIFICATION AMPLITUDE AT EACH LINE LENGTH
C; FOR CURRENT SUBJECT AND COMPOSITE OF PREVIOUS SUBJECTS


;DIMENSION GSX(10),GSX2(10)
100;FORMAT ("SUBJECTS=")
101;FORMAT ("TRIALS PER POINT=")
102;FORMAT (I)
103;FORMAT (E)
104;FORMAT (/,E,E,E,E,/)
105;FORMAT ("POINTS=")
106;FORMAT (/,/)
1;TYPE 100
;ACCEPT 102,I
;TYPE 101
;ACCEPT 102,J
;TYPE 105
;ACCEPT 102,K
;FJ=J
;DO 4 L=1,K
;GSX(L)=0.0
;GSX2(L)=0.0
4;CONTINUE
;DO 2 N=1,I
;FN=N
;TYPE 106
;DO 2 L=1,K
; SX=0.0
; SX2=0.0
;DO 5 M=1,6
;ACCEPT 103,X
5;CONTINUE
;DO 3 M=1,J
;ACCEPT 103 ,X
; SX=SX+X
; SX2=SX2+X*X
3;CONTINUE
;GSX(L)=GSX(L)+SX
;GSX2(L)=GSX2(L)+SX2
; XM=SX/FJ
; STD=SX2/FJ-XM*XM
; STD=SQTF(STD)
;GXM=GSX(L)/(FN*FJ)
;GSTD=GSX2(L)/(FN*FJ)-GXM*GXM
;GSTD=SQTF(GSTD)
;TYPE 104,XM,STD,GXM,GSTD
;TYPE 106
2;CONTINUE
;GO TO 1
;END
```

```
C; PROGRAM TO FIT A CURVE OF THE FORM
C;
C;        A = C1 + C2 * L**C3
C;
C; THROUGH THE INTENSIFICATION AMPLITUDE  VS.
C; LINE LENGTH DATA


;DIMENSION X(10),Y(10),XL(10),YL(10)
100; FORMAT (E)
101; FORMAT (/,E)
102; FORMAT (/,E,E,E,E)
103; FORMAT (/,/)
104; FORMAT (/,E,E,E)
;X(1)=0.078125
;X(2)=0.234375
;X(3)=0.625
;X(4)=1.25
;X(5)=1.875
;X(6)=2.5
;X(7)=3.125
;X(8)=3.75
;X(9)=4.375
;X(10)=5.0
;SXL=0.0
;SXL2=0.0
;DO 1 I=1,10
;XL(I)=LOGF(X(I))
;SXL=SXL+XL(I)
;SXL2=SXL2+XL(I)*XL(I)
1;CONTINUE
;XLM=SXL/10.0
;XL2M=SXL2/10.0
;DEN=XL2M-XLM**2
2;DO 3 I=1,10
;ACCEPT 100,Y(I)
3;CONTINUE
;DO 5 I=1,10
;TYPE 101,Y(I)
5;CONTINUE
;J=-1
;K=0
;N=0
;ACCEPT 100,C
;DEL=1.0
;FINC=DEL
6;SYL=0.0
;SYL2=0.0
;SXY=0.0
;DO 4 I=1,10
;IF (Y(I)-C) 9,9,19
19;YL(I)=LOGF(Y(I)-C)
;SYL=SYL+YL(I)
;SYL2=SYL2+YL(I)*YL(I)
;SXY=SXY+XL(I)*YL(I)
4;CONTINUE
;YLM=SYL/10.0
;YL2M=SYL2/10.0
;XYM=SXY/10.0
;B=(XYM-XLM*YLM)/DEN
;A=YLM-B*XLM
;F=A**2+2.0*A*B*XLM+B**2*XL2M'
 -2.0*A*YLM-2.0*B*XYM+YL2M
;A=EXPF(A)
;IF(N) 16,16,17
17;TYPE 103
;TYPE 102,C,A,B,F
;TYPE 103
;GO TO 2
16;TYPE 102,C,A,B,F
;J=J+1
;IF (J) 8,8,7
18;K=1
8;C=C+FINC
;PF=F
;GO TO 6
7;IF (PF-F)9,9,18
9;C=C-FINC
;IF (K) 11,11,10
10;IF (DEL-0.01) 14,14,15
14;N=1
;GO TO 6
15;DEL=DEL/10.0
;K=0
;FINC=DEL
13;C=C+FINC
;GO TO 6
11;IF (FINC) 10,10,12
12;FINC=-FINC
;GO TO 13
;END
```

APPENDIX F

NOTES ON INTENSIFICATION SIGNAL

by Noel Van Houtte

(This section is a correction and extension of the material described on pages 23-24, 65-66)

F.1 The amplitude of the intensification signal as a function of line length, for a given constant intensity, is

$$A(L) = C_1 + C_2 L^{C_3}$$

The constants were found to be

$$C_1 = 2.42 = 757_8$$

$$C_2 = 1.94 = 615_8$$

$$C_3 = 0.68 = 5256_8$$

These constants were rounded off for computation to

$$C'_1 = 2.500 = 1000_8$$

$$C'_2 = 2.000$$

$$C'_3 = 0.667 = 5253_8$$

The general formula for variation of intensity with depth is

$$A(L,D) = C_1 + C_2 \left[L\left(\frac{D_0}{D}\right)^2\right]^{C_3}$$

Using a law of illuminance

$$I \sim D^{-2}$$

With the constants used for computation:

$$A(L,D) = 2.500 + 2.00 \quad L^{0.667} \left(\frac{D_0}{D}\right)^{1.333}$$

Using the scales for the variables, as indicated on pages 65-66, we obtain

$$A(L,D) = 1000_8 + \text{alog } (2525_8 \log L^2 - 5253_8 \log D^2 + F)$$

where

$$F = \log 2 + 5253_8 \log (300_8)^2 - 2525_8 \log 12.1727_8$$
$$+ \log 315_8$$

$$= 525_8 + 1321_8 - 576_8 + 5075_8 = 6345_8$$

The constants used for the experiment were slightly different:

600_8 for 1000_8

1631_8 for 1321_8

6655_8 for 6345_8

F.2 The physical relationship between beam current (i) and voltage (V) across the grid is

$$i = k\ V^{3/2}$$

Hence

$$V = k'\ i^{2/3}$$

Assuming:

1. that the intensity (I) of a line on the scope is proportional to the number (n) of particles per unit length

$$I = k_1 \; n$$

2. that the number of particles hitting the screen in a given time interval is proportional to beam current (i)

$$nL = k_2 \; i$$

3. that the law of illuminance is inversely proportional to depth squared

$$I = \frac{k_3}{D^2}$$

then the above formula for the voltage across the grid can be rewritten as

$$V = k'' \; \left(\frac{L}{D^2}\right)^{2/3}$$

and for constant depths, i.e. constant intensity

$$V = k'_1 \; L^{2/3}$$

The experimental relationship used is

$$V = C_1 + C_2 \; L^{2/3}$$

The additive constant C_1 is due to the grid circuit of the oscilloscope used. (The oscilloscope intensity knob is set such that the sitting beam is not seen.)

The display system was observed with this form of intensity variation. All lines had the same intensity, not only for all line lengths, but also when intensity varied with depth. The intensity decreased rapidly with depth, and this suggests that a law of illuminance should be taken

$$I = k_3 \, D^{-d}$$

where $d = 1$ or less, instead of the previously used $d = 2$.

REFERENCES

1. Attneave, Fredrick, Applications of Information Theory to Psychology, Holt-Dryden, New York, New York, 1959.

2. Bell Helicopter Company, "Television Eyeglasses See in the Dark," Electronics Digest, July-August 1967.

3. Boring, Edwin G., Sensation and Perception in the History of Experimental Psychology, Appleton-Century-Crofts, Inc., 1942, pp. 268-269.

4. Digital Equipment Corporation, PDP-8 Users Handbook, Digital Equipment Corp., Maynard, Mass., 1967.

5. Freund, John E., Mathematical Statistics, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1962.

6. GPS Instrument Company, The GPS 290T Hybrid Computer Instruction Manual, GPS Instrument Co., Newton, Mass., 1966.

7. Morgan, Clifford T., Introduction to Psychology, McGraw-Hill Book Co., Inc., 1961, pp. 299-330, 293.

8. Roberts, Lawrence G., "Machine Perception of Three-Dimensional Solids," M.I.T. Lincoln Laboratory, Lexington, Mass., Technical Report No. 315, 1963.

9. Roberts, Lawrence G., "Homogeneous Matrix Representation and Manipulation of N-Dimensional Constructs," M.I.T. Lincoln Laboratory, Lexington, Mass., 1966.

10. Roberts, Lawrence G., "The Lincoln Wand," M.I.T. Lincoln Laboratory, Lexington, Mass.

11. Sutherland, Ivan E., "Sketchpad: A Man-Machine Graphical Communication System," M.I.T. Lincoln Laboratory, Lexington, Mass., Technical Report No. 296[U], 1963.

12. Tilton, Homer B., "Principles of 3-D CRT Displays," Control Engineering, February 1966.

13. Vernon, M. D., The Psychology of Perception, Penguin Books, Baltimore, Maryland, 1962.

14. Young, L. R., and Li, Y. T., "Studies of Human Dynamic Space Orientation Using Techniques of Control Theory," M.I.T. Man-Vehicle Control Laboratory, Cambridge, Mass., Seventh Semi-Annual Status Report on NASA Grant NsG-577, June 1967.